PERFORMANCE EVALUATION OF NODE PLACEMENT SCHEMES FOR WATER PIPELINES MONITORING

BY

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عمادة الدراسات العليا
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To the soul of my Mother (Allahs mercy with her).
To the soul of my Father (Allahs mercy with him)
To my brothers and sisters
To my wife and sons

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All praise and glory are due to Almighty Allah (SWT) for his limitless blessings and guidance and may Allah bestow his peace on the prophet, Muhammad (PBUH).

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THESIS ABSTRACT

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Wireless sensor network has proven to be a reliable tool for monitoring applications. Most of these applications expect sensor nodes to operate with the desired level of fidelity for years, especially those deployed for long distance. However, sensors with limited energy budget and sensing range may not be able to meet this expectation. Consequently, node placement is considered one of the most important factors that can cause non-uniform energy consumption, limit the sensing range and shorten the network lifetime. Therefore, sensor nodes should be strategically placed to tackle these challenges. There are many node placement schemes that have been proposed, however, most of these schemes are not applicable for the linear topology (i.e. Pipelines Monitoring). In this thesis, we study node place-

ment approaches of WSNs for pipeline monitoring. Since most of the existing placement approaches are not efficient especially for reliable communication, required fidelity and desired lifetime, we propose two novel placement approaches based on clustering techniques. These approaches gather the sensor nodes based on their power levels to balance the energy consumption among all clusters. The required fidelity is achieved by limiting the distance between sensor nodes such that the monitored phenomenon is caught with confidence. We have evaluated these approaches via simulation and real experimentation. The simulation results demonstrate outstanding performance compared to the greedy approaches in terms of minimizing the power consumption, reducing the number of forwarded packets and increasing the lifetime. Moreover, proof-of-concept experiments using TelosB motes have been carried out for validating the proposed approaches.

ملخص الرسالة

الاسم الكامل: عبداللطيف محمد عبدالله البصير

عنوان الرسالة: تقييم أداء طرق التوزيع المستخدمة في شبكات مراقبة تسريب انابيب نقل المياه

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استخدام شبكة الاستشعار اللاسلكية أصبح مشهورا بالآونة الأخيرة نتيجة للتطبيقات التي تتيحها في مختلف المجالات. فشبكة الاستشعار اللاسلكية تستخدم في العديد من التطبيقات سواء المدنية او العسكرية مثل تطبيقات البحث والانقاذ والتنبؤ والمراقبة ... الخ. وإن مراقبة خطوط الأنابيب سواء أنابيب الماء أو الزيت واحدة من هذه التطبيقات حيث يتم وضع أجهزة الاستشعار بشكل خطي على طول هذه الانابيب. لكن، طبيعة الاتصالات في هذه الطوبولوجيا تتطلب اهتماماً ودراسة متعمقة نظرا لتباين المهام من الحساسات القريبة من وحدة المراقبة لتلك البعيدة منها. حيث تستهلك الحساسات القريبة من وحدة المراقبة كمية كبيرة من الطاقة لأنها تعمل على تمرير جميع البيانات القادمة الى وحدة المراقبة مما يؤدي الى خروجها عن الخدمة بشكل سريع بينما يقل استهلاك هذه الطاقة كلما بعدنا من وحدة المراقبة. رغم وجود دراسات عديدة في هذا المجال الا انها تعاني من بعض العيوب المتعلقة سواء بعمر الشبكة او عدم تقديم نظام اتصال موثوق أو عدم توفر الدقة المطلوبة في عملية اكتشاف التسريب بسبب بعد بعض العقد عن البعض الأخر بمقدار كبير لا تستطيع الإشارات الصوتية الوصول الى هذا المدى في حال فشلت العقدة المعنية بذلك، ولهذا قمنا باقتراح طرق جديدة للتوزيع مرتكزة على مبدأ التجميع.

الطريقة الأولى تسمى الطريقة متساوية المسافات متساوية الأعضاء والمرتكزة على توزيع العقد على طول الأنابيب بمسافات متساوية وتجميع كل عدد منها كمجموعة واحده لها قائد يسمى رأس المجموعة وهو المسؤول عن تمرير الرسائل المرسلة من مجموعته الى المجموعات الأخرى باتجاه وحدة المراقبة. هذا الرأس يتم اختياره بشكل دوري لتوزيع الحمل مع الوقت بين هذه العقد. والطريقة الثانية تسمى متساوية المسافات مختلفة الأعضاء. حيث يتم تحديد عدد أعضاء مختلف في كل مجموعة بناء على التسوية في استهلاك الطاقة بين بين جميع التجمعات (Clusters). ولدراسة كفاءة هذه الطرق، تم دراسة الطرق المقترحة باستخدام المحاكاة وباستخدام تجارب واقعية على حساسات من طراز (TelosB) وجميعهم اثبتوا فعالية الطرق المقترحة.

CHAPTER 1

INTRODUCTION

Before describing the fundamental research topic, an introduction to Wireless Sensor Networks (WSNs), especially those used for monitoring applications, is introduced to make the reader familiar with the concept of this type of networks. Later, the explanation for WSNs used for pipelines monitoring also is presented.

1.1 Wireless Sensor Networks

The rapid improvements in Wireless Sensor Networks (WSNs) as well as their fast deployments at low cost and with high flexibility, in the last ten years have brought great opportunities to be applied in many fields in our real-life, such as Environmental/Habitat monitoring, acoustic detection, seismic detection, disaster managing, security surveillance, nuclear, biological and chemical attack detecting, medical monitoring, wildlife tracking etc. [5][6][7].

Typically, WSNs involve a large number of spread sensor nodes assigned to monitor/perform particular events and the deployment of these sensors might be in

unstructured approach (no any infrastructure support for this type of the networks) or might be in a structured approach (infrastructure support) [8][9].
A prominent type of such applications of a structured approach in WSNs is the on-line pipelines monitoring which is used to detect the anomaly of these pipelines. The capabilities of WSNs to provide a continuous monitoring of these pipelines are unsurpassed with the participation of the Administrative humans.

Detecting the problems in the early stages will enable the authorities to take preliminary precautions and guarantee the public safety and protecting the environment. For example, detecting the leak in water pipelines could prevent major effects that may lead to financial loss and damage to peoples health. [10]. Similarly, this type of application can be applied for detecting the leaks of risky material at the early stages such as natural gases and crude oil which possibly will cause pollution and the eruption of fires. [11]. However, this type of WSNs requires a certain attention because the sensor nodes are placed linearly, which brings many challenges related to routing, traffic management, lifetime, power consumption etc.

In addition, the limited resources of the deployed sensor nodes in terms of memory size, computational power, battery capacity, transmission ranges and sensing ranges bring many challenges to be considered [12]. Among these issues, the energy consumption problem and limitation of transmission ranges are the main points of interest. In most sensors, the equipped non-rechargeable or non-replaceable batteries result to shorten the network lifetime. Hence, designing reliable and long-lived WSNs is essentially important and challenging issue because the positions of sensor nodes significantly influence the overall operation of a WSNs [13][14][15].

1.2 Review on WSNs for Pipeline Monitoring Applications

Before introducing the WSNs as a novel solution for leakage detection, it is crucial to understand the ways of how the water is transported and the importance of monitoring the pipelines used for this purpose. Typically, in the modern world, water pipelines are distributed for a long distance up to hundreds of kilometers to transport water from a water reservoir to a metropolis. The system of water pipelines consists of large scale sealed pipes that are buried in soil as depicted in figure 1.1 or exposed directly to air as Figure 1.2 illustrated.

Figure 1.1: Underground water pipelines[2]

Figure 1.2: Above-ground water pipelines[3]

For example, In Saudi Arabia, the largest desalinated water producer in the world, long pipelines are used to transfer the water from the Shoaiba Desalination Plant in Al-Jubail, a city in the eastern province of Saudi Arabia, to Riyadh. [6].

The leaks in these pipelines may occur suddenly or gradually affected by a combination of several factors. Thus, these pipelines need to be permanently monitored in case of a sudden leak caused by significant outside force. If a leak is not detected in time, significant environmental damage, commercial loss, or health hazard may occur because the drinking water can be easily contaminated by bacteria in soil or anything surrounding these pipelines[16]. Furthermore, it is necessary to detect the leak when it is still small to avoid a leak leading to a break consequently and the commercial loss could be reduced.

To avoid these problems, the WSNs has been adopted as a reliable tool to monitor these pipelines in order to detect any potential leaks or damages.[17] [18]. In the pipelines monitoring, the WSN utilizes hydraulic, water quality and acoustic/vibration data to inspect these pipes and the Global Pointing System (GPS) and Precise Positioning Service (PPS) are used to synchronize the whole system.

Generally, the collection and aggregation of data in WSNs, used for water pipelines monitoring are performed using multi-hop forwarding schemes. In these schemes, the sensor nodes are deployed linearly, and all sensor nodes should sense and report to the base station regularly, at predetermined intervals. Therefore, aggregation data of the nodes farthest from the base station should pass to all other intermediate nodes leading to unevenly power consumption due to highly asymmetric traffic on the nodes closest to the base station following a many-to-one model, where these nodes convey heavier traffic loads [7]. This is apt to extremely decrease the sensor networks lifetime. Thus, sensor nodes should be strategically placed to prolong the lifetime of the network. To tackle this problem, more sensor nodes can be deployed closer to the base station and transmit/carry data at lower power levels [8][13] to expand the network lifetime.

Recently, many research works [18, 19, 16, 20] have focused on the deployment of sensor nodes for pipelines monitoring, including node placement problem in terms of connectivity, fidelity, coverage, or a lifetime. Few of these works are on how to maximize the lifetime either by deploying auxiliary nodes for transmitting or by suggesting energy harvesting approaches [14].

Some of these works also have investigated this problem by finding the relationship between the distances (transmission ranges) and the transmission power levels using continuous ideal power model[21] [22] [7] [23].

Very few of these studies [20], [24] have adopted a realistic power model when this problem has been considered. However, these works only have adopted the documented power levels and no one of these works has taken into account all-discrete power levels. In addition, most of these works have not taken into consideration the receiving power and the fidelity of the collected data which in turn affect significantly the whole network operation [25].

1.3 Motivations

As stated earlier, Wireless sensor networks have proven to be a good candidate for many monitoring applications such as habitat monitoring, structural health monitoring, etc [26][27]. Pipeline monitoring is another application where sensors are placed in linear topology [16]. This linear topology requires careful attention in placing sensors to minimize the energy consumption and maximize the network lifetime. In such case, one of the fundamental design issues for WSN used to monitor water pipelines, is where the nodes are to be placed in order to effectively handle the application requirement and enable efficient operation. In general, the positions of sensor nodes significantly influence the performance of any WSN and its performance metrics such as power consumption, lifetime, fidelity, and coverage. In this work, we are going to tackle such challenges.

Furthermore, assuming similar initial energy budget for all sensor nodes, the sensor nodes near the base station quickly deplete out their energy because their heavier responsibilities in addition to data forwarding from far sensors nodes and hence shorten the network lifetime. In other words, the lifetime of this type of WSNs primarily depends on the sensor nodes closest to the base station because the failure of such nodes will prevent other sensors to send their data to the control unit. There are also interesting challenges related to the node placement problem. For example, it is important to assure the desired level of data fidelity.

This thesis investigates the node placement problems by analyzing the shortcomings of existing approaches and proposing new power-efficient placement approaches to deploy the sensor nodes with less complexity, higher fidelity and longer lifetime.

1.4 Thesis Contribution

The goal of this thesis is to propose novel node placement schemes that can significantly improve the network performance by maximizing the lifetime and obtaining the desired fidelity then these approaches are evaluated using a realistic power consumption model. The contributions can be summarized in the following points:

1. We propose exploiting the power levels that are equipped with the CC2420 power model to effectively prolong the network lifetime. So, we suggest using all 31 power levels to balance the energy consumption.

2. We have run a real experiment to measure the exact range of such power levels due to unavailability of real measurements of these power levels.

3. We improved the performance of the greedy approaches to optimize the power levels assigned to every sensor node. There are two suggested heuristics addressed in [8] to find out the optimal number of sensor nodes and their power levels. The idea is to assign the maximum power level to the nodes furthest from the base station and reduce the power levels for the nodes closest to the base station.

4. To overcome the shortcomings of the greedy heuristic approaches, we propose a clustering approach called equally-distance equally members to dynamically, balance the consuming power as well as assure the required fidelity. In this algorithm, every sensor node can serve as a cluster head in their group and be in charge for a fixed period to send the data for all members in its group to another adjacent cluster head and so on until reaching the base station. Only the elected cluster head individually, sends the data with maximum transmission power P_C. Other nodes set its transmission

power to power level $< P_T$. In more details, our proposed model consists of n nodes that must be enough to cover the desired pipeline length and these nodes need to be cooperatively grouped and select one from each group to be a cluster head. The distances between sensor nodes should be in the ranges that allow detecting the leak by more than one sensor to get the desired fidelity. In each group, forwarding the data as the normal situation (each node sends to its neighbor then to the cluster head of the group). The cluster head is selected alternatively to balance the energy consumption and based on the energy available.

5. Moreover, we improved the performance of clustering approach by assigning unevenly members in each cluster to increase the lifetime of the clusters nearest to the BS. This approach is called equally-distance different members.

6. We have validated our approaches by conducting simulation and real experiments to study the performance of such approaches. The TelosB motes are adopted for testing these proposed approaches.

1.5 Thesis Organization

The remainder of the thesis is organized as follows. Chapter 2 presents the state-of-the-art of related works. Anomaly Resilient Node Placement Approach for Pipelines Monitoring is presented in chapter 3. We present the proposed

Clustering-based node placement approaches in chapter 4 and 5 respectively. The thesis ends up with major findings and future directions in chapter6.

CHAPTER 2

LITERATURE REVIEW

In this chapter, we have explored the related work in the field of node placement problems in WSNs. Then limitations and research challenges of current node placement approaches are discussed.

2.1 Previous Studies

In the following section, we present some placement approaches that are classified as in Figure 2.1.

The advanced in WSNs has been exploited to monitor water, oil and gas pipelines in order to detect the probable leaks[17] [18]. This type of network utilizes hydraulic, water quality and acoustic/vibration data to detect and locate the leak and uses Global Pointing System (GPS) and Precise Positioning Service (PPS) to synchronize the whole system. As the author [28] claimed.

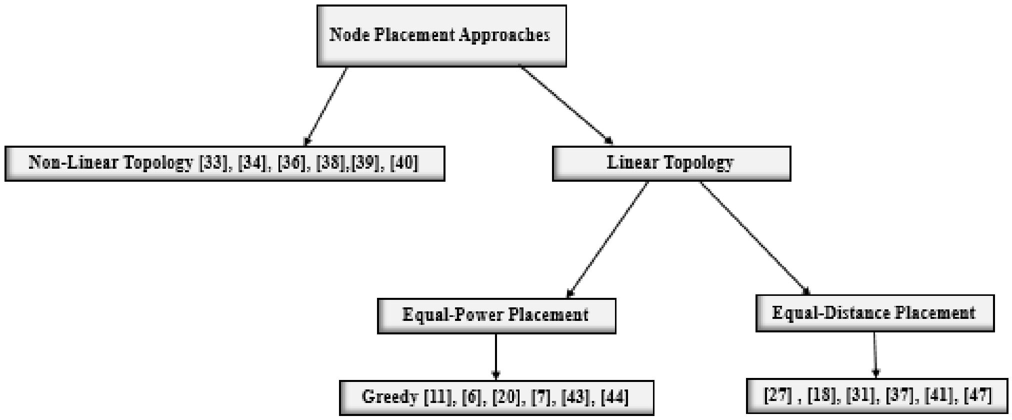

Figure 2.1: Classification of the current node placement schemes

Maglaras and Katsaros have studied applying the WSN to detect the leak in the pipelines. They concluded that such systems basically depend upon the fluid transporting and the environment in which these pipes are placed [29].

Hunaidi and Chu [30] studied the physical characteristics of the leak signals in the pipelines. They proved that the leaks generate acoustic sound waves which the sensors can detect the leakage by inspecting these signals. However, these acoustical signals travel across the pipeline for a limited range because these signals decrease exponentially with plastic or concrete pipes.

The work in [31] introduces a description of the principles of the pipeline's leak detection system. The studied system was designed based on sensing the pressure waves generated by the leaks.

In [19], the authors have studied the fluid leakage in pipelines. They eventually addressed the related issues with four different solutions using WSNs. The

WSN-based solutions were magnetic induction based, continuous monitoring for pressure, underground to above ground radio propagation and wireless signal networks. Ultimately, they concluded that after introducing the theoretical structure for magnetic induction-based, deploying this system in real-life needed much work especially, in the deployment stage. Advantages and disadvantages are always present and these techniques were useful to avoid pipelines leakages due to their real-time detection. However, the node placement problem still the most dominant berries in designing and operating such systems.

In [32] authors proposed a control system to monitor the gas pipelines. This system is based on low-power MSP430 microcontroller and XBee techniques. The sensor nodes are deployed in the intended area and each sensor node collects the data and periodically reports to the monitoring unit or to the specialized user to update the data. Data packets are continuously transmitted from sensor nodes and communication devices. However, the lifetime and the energy consumption have not considered in this study.[33].

Node placement problem in WSNs, in term of on the energy consumption, fidelity and lifetime, has been widely studied and investigated by many researchers in the past ten years.

In [34], the study of determining the optimal locations of the relay nodes has been investigated by Ergen and Varaiya. They have considered the energy constraints with the desired lifetime. A non-linear programming model has been established to determine the possible locations of the relay nodes. However, their work was performed on non-linear WSNs (on the grid positioning) and the required fidelity and the cost constraints have not studied.

In [35], unevenly consumed energy is identified in many-to-one sensor networks and to address this problem, the authors have proposed mobile sink and hierarchical structure. The mobile sink keeps moving to collect the data from the nodes in the networks.

Tran et al [36], have proposed a joint network coding and adaptive power control scheme to reduce the total power consumption and increase the bandwidth usage by regulating the transmission power. They claimed that their approach has shown effective results compared to an existing technique.

Meanwhile, Chuan et al.[37] have suggested taking advantage of aggregation and compression technique in order to reduce the amount of data sent. They concluded that the less data sent, the more energy conserved. However, the sensor nodes closer to the base station consume more power because they should do more processing and transmitting tasks.

Instead of using In-network processing scheme as in previous work, Wei et al. [38] have proposed a protocol to define the coordinated schedules for sleep/wake-up states between sensor nodes in WSN. In this work, the time point for the node to change its state from idle to busy is determined by wake-up strategy and vice-versa. But even with this technique, the nodes located besides the BS still consume the most energy and die quickly.

In [39],[40], the authors have proposed an approach to use an extra number of relay nodes for relaying tasks only. They tried to optimize number of these nodes. They have proven that this problem is NP-hard and derive a lower bound on the minimum number of sensors is required so they design an algorithm to select the proper number of the relay nodes. They concluded that using the relay nodes provides a significant lifetime. However, the problem is still consuming more power in the relay nodes besides the base station.

In recent years, a considerable attention has been devoted for node placement in linear topology (i.e. pipelines monitoring systems).

Joonhyo el al. [41] have considered sensors placement on highways to assess vehicular flow and the travel speed. They concluded that increasing the node population at the merge exits and splits are recommended in order to cope with the variability of the traffic pattern. Nonetheless, full coverage is needed and the presence of blind spots between sensors is acceptable. However, most of these works are inapplicable to linear WSN due to the characteristics of this topology.

In [42] authors have suggested an algorithm that supports the proper selection for the relay sensor nodes placement and accordingly select the transmission power levels of sensor nodes that provide the maximum lifetime. However, these studies have not taken into consideration the sudden damage and inspecting the pipelines are temporary.

In [43], authors proposed an algorithm to determine the data collector optimal placement and find the optimal paths to carry out the data from underwater sensors to the onshore data collector. Also, this problem has been modeled as an integer linear programming.

Similarly, Guo et al.[8] have studied the node placement problem for oil pipelines monitoring under two node placement schemes, equal-power and equal-distance node placement scheme. They have proposed two heuristics to properly distribute the sensor nodes based on their power levels with a view to maximizing the lifetime by appropriately increase the density of the sensor nodes closer to the base-station and configure these nodes to carry/transmit the data at lower power levels. They have also suggested a mathematical model, validate their heuristics and their results showed that the network lifetime could increase up to 29% compared to equal distance placement approach. However, they only have used 6 of 31 power levels and their focusing was only in the transmission power.

In addition to, Djame et al. [44] take advantage of energy harvesting capabilities. Generally, they have proposed to use harvesting-enabled sensor nodes for only relaying the packets and non-harvesting sensor nodes, used for sensing and transmitting their readings to relay sensor nodes.

Furthermore, related to node placement on pipeline monitoring, a non-uniform scheme called linearly decreasing distance (LDD) has been presented by [45]. LDD gradually, reduces the distance among sensor nodes and the placement of these sensor nodes is placed near to the gateway.

In [40] a constrained multivariable nonlinear programming problem has been formulated. The results show that the performance of the optimal node placement strategies is better than uniform node placement strategies.

Moreover, Zhang et al [46] have studied the lifetime and energy consumption in linear WSNs used for transportation safety monitoring. They suggested a network architecture with several sink nodes. They proposed to and proposed a method to determine the sink node number in a group and network forming scheme. They Claimed that their scheme can increase significantly compared to the equal-distance scheme. However, they did not consider the power consumption of the sensor nodes in each segment.

In [47], Alduraibi et al have studied the coverage problem when the event detectability varies with proximity to the sensor and some desired level of sensing fidelity is to be maintained. Three optimization models have been presented to determine the node density. They have concluded that their proposed models meet their respective design objective.

Authors in [48] have investigated the node placement problem in linear WSN used for structural health monitoring under with an objective to maximize the network lifetime. A methodology to find the optimal placement for the sensor nodes in this topology. They have concluded that their methodology saves the energy and extends the sensors lifetime.

2.2 Conclusion

Having discussed the works in the literature, node placement problem in WSNs has been widely investigated However, few of them only has been devoted for pipeline applications where the sensor nodes are deployed linearly. Moreover, few of these studies have adopted a realistic power model; no available work has considered all-discrete power levels. In addition, most of these works came up with greedy heuristic approaches which increase the density of sensor nodes with lower power level nearest to the base station. Also, all sensor nodes are responsible for carrying out the packets towards the BS All the time. Moreover, these solutions practically do not introduce the reliable communication because the access can only be in one way because the ranges of sensor nodes are varied and based on their location. Moreover, most of these previous works did not consider the required fidelity.

CHAPTER 3

ANOMALY RESILIENT NODE PLACEMENT APPROACH FOR PIPELINES MONITORING

In this chapter, we critically study equal-power node placement schemes by adopting a realistic power model and analyzing their performance based on both the transmission power and reception power. Predominately, we investigate the CC2420 power model and its equipped power levels to measure their transmission ranges. The real experiment has been conducted to measure the exact transmission range. Then, we investigate two efficient greedy heuristic schemes while using the documented 8 power levels or all 31 power levels. The performance of each placement scheme is validated through extensive simulation and real experiments. The results demonstrate the effectiveness of these schemes in case of using all 31 power levels compared to using only the 8 documented power levels. The main contributions of this chapter are:

- conducting a real measurement of the transmission ranges of all power levels equipped with CC2420 power model.
- Improving the greedy placement schemes which are proposed on [4] based on our measurements.
- Evaluating the performance of these schemes by applying the obtained distribution on simulation and real experiments.

3.1 Greedy Heuristics Schemes

To balance the energy consumption effectively among the deployed sensor nodes, two heuristics have been suggested by [4]. In this scheme, the sensor nodes are grouped based on their power levels. The sensor nodes set to the lower transmission power level are placed closer to the base station and the sensor nodes set to higher transmission power level are placed far away from the base station. All sensor nodes grouped to one dimension vector V. The output vector V is built by one of the proposed heuristics and it includes all sensor nodes distributions.

Our improvements for these schemes are as following:

- The receiving power is included in the total power calculation; it has a high impact on total power consumption and network lifetime.

- Adopting 31 power levels instead of 6 power levels mentioned in [4].
- The total energy consumption is computed.

Now, we present a brief description of the mechanism of low to high and high to low heuristics and we provide an explanation of our proposed clustering algorithm.

3.1.1 Low To High Heuristic

In this heuristic, initially, as explained in [8], all sensor nodes are assigned to the minimum power level p1. Hence, the output vector V initially, is $< n, 0, , 0 >$. If the sensor nodes can cover the length of the pipeline, they are set to transmit at this power level. Otherwise, the power level of the node consumed, the less energy is increased. This procedure is repeated until no improvement in the lifetime or the coverage. Algorithm 3.1 explains all steps for assigning the power levels for all sensor nodes based on their locations

Table 3.1: Low to high heuristic

Algorithm 1 : Expansion L-to-H Heuristic Algorithm

Input: *n, L,* R_x*, and (*P_j *,* R_j *) with j = 1, . . . , m;*

Output: *power level assignment vector V;*

if $(n \;\; R_m < L)$ ***then***

    exit: the number of nodes is not enough

end if

Initialize $V =< n, 0, . . . , 0 >$;

While The sensor nodes ranges don't cover the pipelines length ***do***

    Compute E^{min}

     For all power levels except P^{max} *do*

        compute the E^{temp} //to be compared with E^{min}

          if (This power level is assigned and $E^{tmp} \leq E^{min}$*)* ***then***

            $E^{min} = E^{tmp}$ *;* $x = i$;

          end if

     end for

    Update assignment vector: $V_x - = 1$; $V_x{+}1{+} = 1$;

end while

3.1.2 High To Low Heuristic

In this approach, all sensor nodes are assigned to the maximum power level p_m. Consequently, the output vector V initially, is$< 0, , 0, n >$. Then, the power level is reduced. This procedure is repeated until no improvement in the lifetime or the coverage.

Table 3.2: High to low heuristic

Algorithm 2 : contraction H-to-L Heuristic Algorithm

Input: *n, L, and* (P_j, R_j) *with* $j = 1, \ldots, m$;

Output: *power level assignment vector V;*

if $(n \ \ R_m < L)$ ***then***

  exit: the number of nodes is not enough

end if

Initialize $V = <0, 0, \ldots, n>$;

While *The sensor nodes ranges are still longer than the pipelines length* ***do***

  Compute E^{max}

  For all power levels m ***do***

    Compute E^{tmp})

    if (This power level is assigned and $E^{tmp} \geq E^{max}$*)* ***then***

      $E^{max} = E^{tmp}$; $x = i$;

    end if

  end for

  if $(x == 1$ *or* $\sum_{i=1}^{m} (V_i.R_i) < L + (R_x - R_x - 1))$ ***then***

    break;

  else

    Update assignment vector: $V_x - = 1$; $V_{x-1} + = 1$;

end while

3.2 Telosb Mote

TelosB is a platform designed for low power sensor network applications. It uses CC2420 radio chip with transmission speed of 250 kbps and works on 2.4 GHz radio frequency.

3.2.1 CC2420 Power Model

In this work, we adopt the CC2420 RF transceiver CC2420 power model as a reference because it provides reliable wireless communication and can be configured to opt with many applications. This model has been adopted by many researchers in oil and gas pipeline leakage detection system [49][20]. According to the CC2420 datasheet, the programmable output power range is 31 levels. Only 8 output power which are 3,7,11,15,19,23,27,31 respectively, are documented as mentioned in [1]. However, using the CC2420 driver of Tiny-Os-2.x, 31 different values are active and can be exploited.

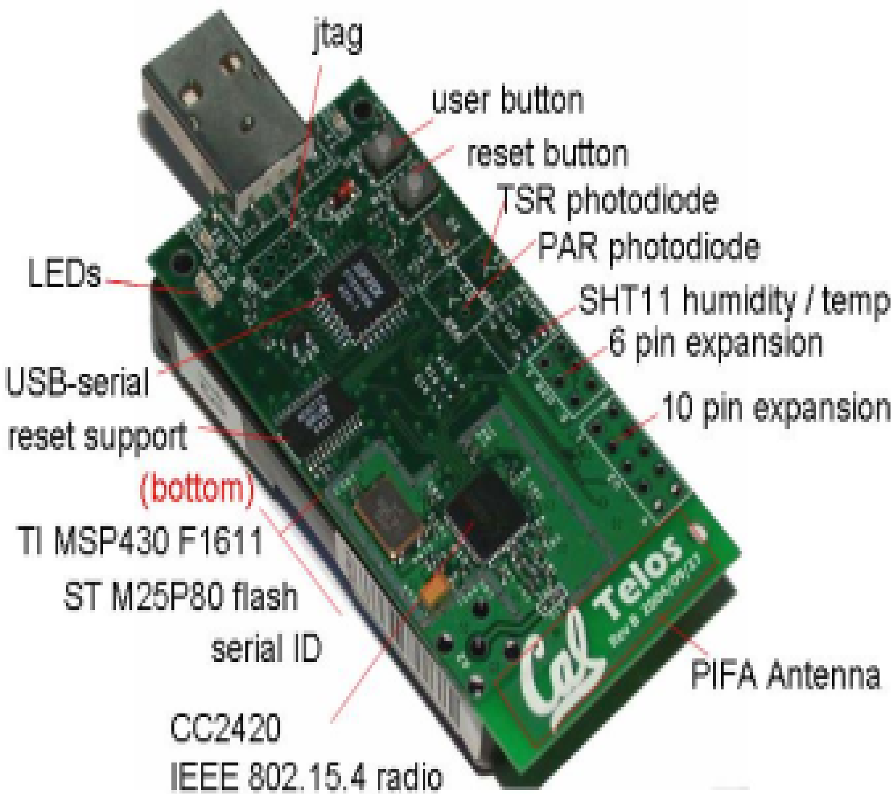

Figure 3.1: TelosB mote specifications [4]

3.3 Pipelines Network Architecture

As pointed out, we consider the WSN, used for water pipelines monitoring, consists of segments. Every segment with length L comprises of several sensor nodes that are placed linearly along the pipelines and this segment ends with a base station that aggregates and summarizes the data. To simplify, we consider a WSN is a single segment as depicted in Figure 3.2. After the deployment is achieved, the sensor nodes sense within their ranges and periodically report to the base station through multi-hope scheme (i.e. a sensor node forwards the data to its adjacent node towards the base station path). The signals assumed to be acoustic so the maximum distance between the sensor nodes must be within the range that allows being heard. In addition, we assume more than one sensor node hears the leak and report to increase the reliability.

Let n be the number of sensor nodes covered the pipelines length L and m is the number of power levels that are supported by all sensor nodes, the distance between i_th node transmit at power level j and $(i + 1_th)$ node transmit at power level $j + 1$ is d_i which represents the transmission range of sensor node i, where $i = 1, 2, 3, , n$ and $j = 1, 2, 3, , m$. To ensure that the length of the pipeline is covered the distances between all sensor nodes must be equal the length of the intended pipeline. For simplicity, it can be expressed as follows:

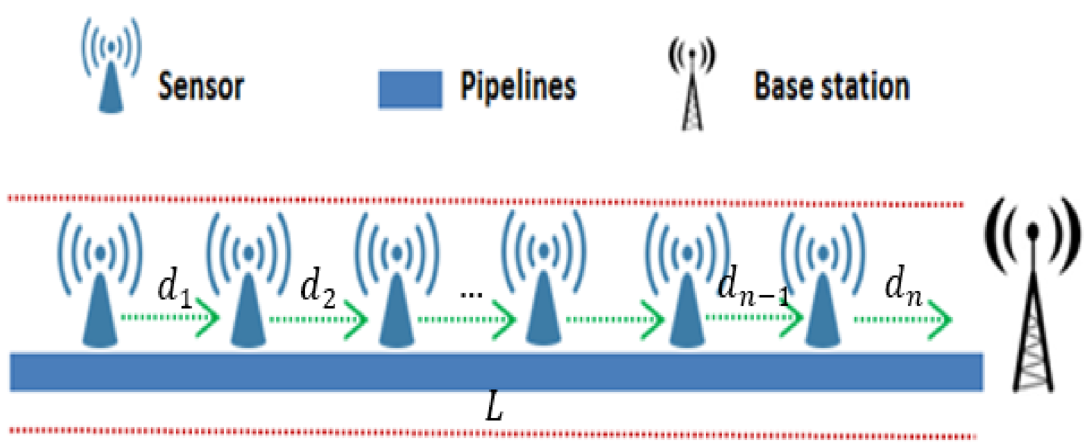

Figure 3.2: Network architecture

$$\sum_{i=1}^{n} d_i = L \tag{3.1}$$

3.3.1 Energy Consumption Model

To calculate the network lifetime, the energy consumption should be determined. The energy consumption model used in [8] has been adopted and extended to involve the receiving power due to its high impact on total energy consumption. It is well-known that the transmission ranges of the sensor nodes depend on the transmission power. Thus, the sensor node N_i is set to transmit at power level j has a transmission range R_j. So, the total energy consumption of node N_i required to transmit and receive its packet and all arrived packets is modeled as:

$$E_i = i.P_T.t + (i-1).P_R.t \tag{3.2}$$

where R is the measured values as explained before and the power required for transmitting is P_T, while the power required for receiving P_R is fixed at all power levels and t is the time that the sensor node needs to transmit or receive.

Typically, in this work, we have adopted a TelosB mote as a case study to compute the network lifetime. The TelosB mote specification is depicted in figure 3.1 Also, the lifetime can be computed as:

$$LTbased_i Rounds = \frac{E_{budget}}{E_i} \tag{3.3}$$

where E_{budget} denotes to the initial capacity of the battery of $node_i$ and E_i is the total energy consumption of the sensor node N_i in one round.

Also, the required transmission power of a certain power level is modeled as:

$$P_j = V.I.t \tag{3.4}$$

Where V is the battery voltage and I is the current consumption of the transmission power at level j and it is documented in the CC2420 data-sheet.

In addition, the required receiving power is expressed as:

$$P_R = V.I.t \tag{3.5}$$

Where I is the current consumption of the receiving power which equals to $18.6mA$ as documented in the CC2420 datasheet and t is the time that the node needs to receive one packet.

3.4 Experimental Measurements of The Transmission Ranges

In WSNs, the transmission power of the sensor node affects directly, its transmission range. Hence, due to no ready measured ranges of the 31 different power levels that are supported by CC2420 RF transceiver, we have run a real experiment to measure the proper transmission range of each level.

3.4.1 TinyOS

It is an open-sourced, component-based operating system first developed by University of California in Berkeley [50]. The community of TinyOS development has grown to thousands of developers since its first release in 2000. The development and maintenance are now performed by TinyOS Alliance. TinyOS uses nesC as the official programming language. NesC is a dialect of C programming language, optimized for memory constrained devices [51]. TinyOS programs are built with components. All the events, tasks, and interfaces are considered as computational abstractions of components. There is a set of basic components defined by TinyOS. These components relate to each other through interfaces. Tasks are usually posted to the system scheduler for execution without interrupting the normal system work since TinyOS is a non-blocking operating system.

3.4.2 Experiment Setup

The experiment has been conducted using the following components:

- Two TelosB motes, one as a sender and another as a base station.
- The antenna height is 80 cm for both, the sender and the base station, to avoid soil absorption signals.
- Oscilloscope Application: this application has been modified to monitor and stores sent/received messages. Reading are stored and then transmitted every 250 ms.

Figure 3.3 illustrates the ranges measurements experiment procedures

Figure 3.3: Transmission ranges measurements

3.4.3 The Performance Evaluation Metric and Results

The packet delivery ratio (PDR) has been used as a metric to select the appropriate transmission range based on the higher PDR.

$$PDR = \frac{the\ number\ of\ successful\ received\ packets}{the\ total\ number\ of\ sent\ packets}$$

Table 3.3: Reference table for all power levels and transmission ranges

Power Level	Transmission Ranges (meter)	Power Level	Transmission Ranges (meter)
1	0.4	16	62
2	1	17	66
3	6	18	69
4	8	19	70
5	20	20	73
6	26	21	75
7	30	22	78
8	32	23	79
9	35	24	80
10	42	25	82
11	50	26	83
12	52	27	86
13	53	28	88
14	55	29	90
15	60	30	92
31		95	

For each power level, different distances have been examined to select the proper transmission range that achieve highest PDR as depicted in 3.4 which show the PDR of the last three power levels 29,30 and 31 respectively. Then, the extensive obtained experimental data has been analyzed. The adopted transmission range associated with the certain power level has been selected if the PDR is greater than 95%. Accordingly, the results show that the less transmission range is 40 cm at power level 1 and can reach up to 95 m at power level 31 as depicted in Table 3.3, which shows all power levels associated with their proper transmission ranges.

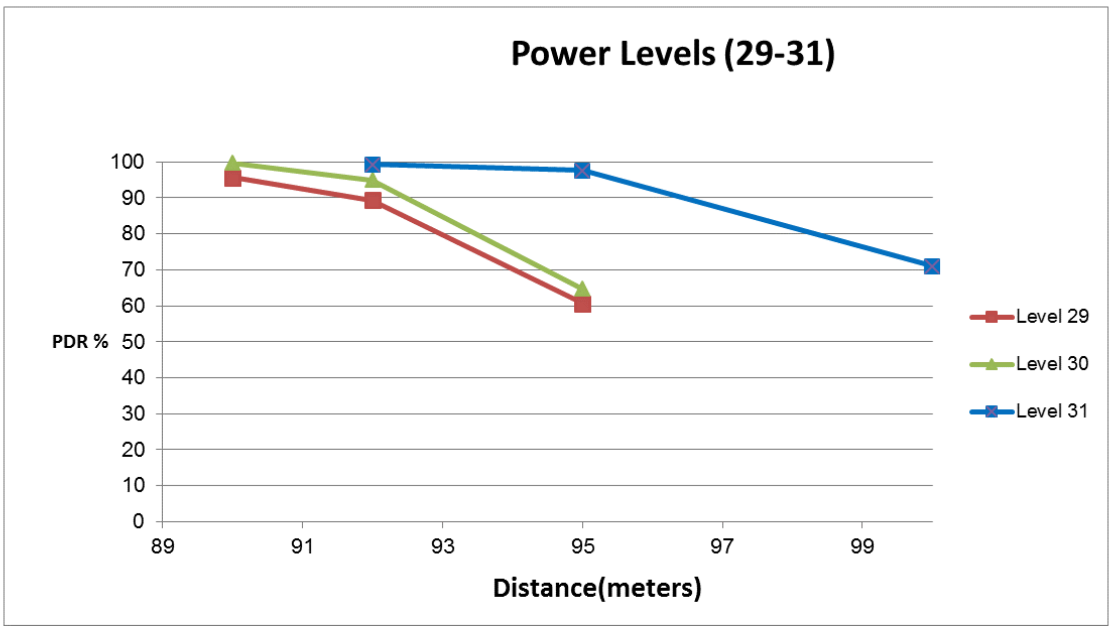

Figure 3.4: PDR performance for (29-31) power levels

3.5 Evaluation and Discussion

In order to evaluate the proposed algorithms, extensive simulation experiments have been conducted to study the effectiveness of each approach. The lifetime and the total energy consumption have been adopted as comparison metrics. The following sections describe the simulation setup and the evaluation metrics and discusses the results.

3.5.1 Simulation Setup

MATLAB has been used to simulate the proposed approaches using the parameters in Table 3.4. The minimum number of sensor nodes and the maximum number of sensor nodes is determined by dividing the length of the pipeline over the maximum transmission range R_{max} and the minimum transmission range R_1, respectively.

Table 3.4: Simulation parameters

Parameter	**Value**
Simulation Tool	MATLAB
The pipelines length	5000 m and 10000 m
The number of sensors sensor nodes	Start from n=L/R_{max}
Battery capacity	2600 mAh
Battery Voltage	3 V
The time of sending/receiving one packet t	5 seconds
Receiving power R_x	0.0564 Watt [24]

We compare the performance of low to high and high to low heuristics using realistic CC2420 power. We compare the commonly used 8 power levels and all

31 available power levels. Two scenarios have been implemented when the length of the pipeline is 5000 m and when the length of the pipeline is 10000 respectively. In the first scenario $L = 5000$, the number of sensor nodes starts from 53 which is the minimum number to cover the pipeline length. In the second scenario, for $L = 10000$, the number of sensor nodes starts from 106.

3.5.2 Evaluation Metrics and Results

The analyzed performance metrics that have been used in this study are:

1. The lifetime*:* the last node of each group determines the lifetime of its group. Consequently, the lifetime of the whole network is the lifetime of the group that earlier goes out of the service. Hence, the lifetime of every group can be formulated as follows.

$$LTGroup_i = \frac{E_{budget}}{(\sum_{k=1}^{i} V_i).P_i.t + (\sum_{k=1}^{i} V_i).R_x.t} \tag{3.6}$$

$$lifetime = min\{LTGroup_1, LTGroup_2, \ldots, LTGroup_m\} \tag{3.7}$$

2. Total energy consumption: the total energy consumption is computed by calculating the energy consumed by all grouped sensor nodes over the whole pipelines. It can be formulated as follows.

$$Total_E = \sum_{i=1}^{V_1} E_i + \sum_{i=1}^{V_2} E_i + \cdots + \sum_{i=1}^{V_m} E_i \tag{3.8}$$

Where V_1 is the sensor nodes assigned to level 1 and V_2 is the sensor nodes assigned to level 2 and so on to m.

Based on these metrics, the simulation results for both cases (i.e. L=5000 or L= 10000) show that using 31 power levels can improve the network lifetime by 23% compared to those using the 8-power levels, as depicted in Figs. 3.5 and 3.6, respectively. This is due to the high granularity in selecting the power level. In addition, the total energy consumption is reduced by 23% when all 31-power levels are considered, as depicted in Figs. 3.7 and 3.8. In addition, Figs. 3.7 and 3.8 show that the sensor nodes using (LTH approach) 31-power levels distribution consumes the least energy due to starting node assignment with lower power level.

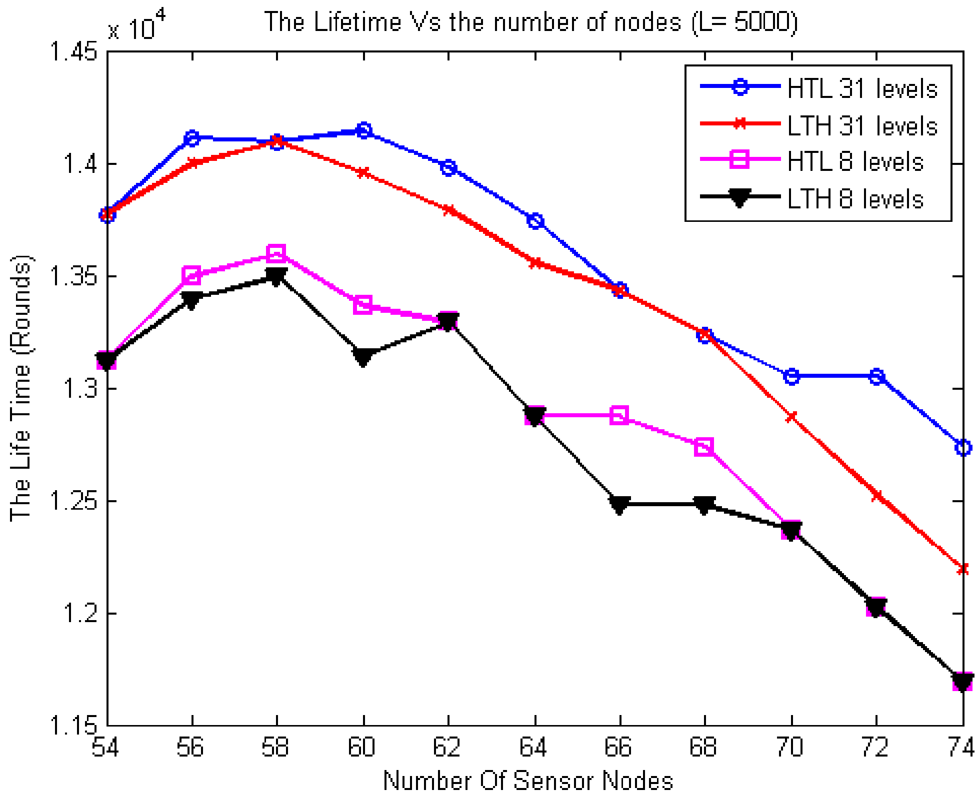

Figure 3.5: The lifetime using 31-power levels and 8-power levels when the length of the pipeline equal 5000 m

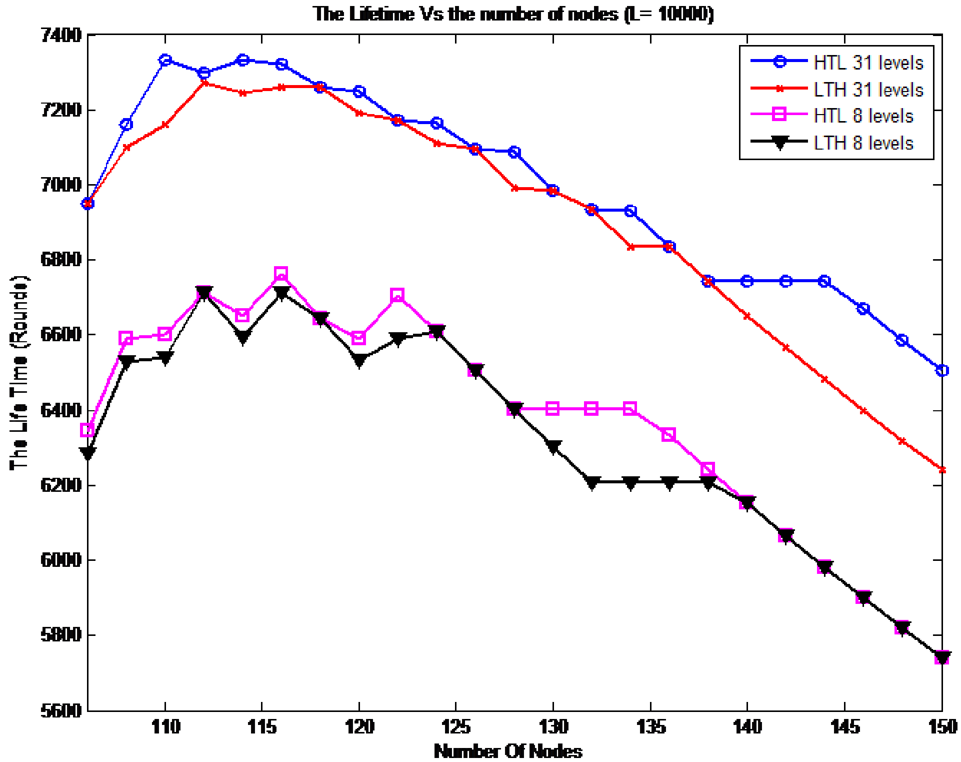

Figure 3.6: The lifetime using 31-power levels and 8-power levels when the length of the pipeline equal 10000 m

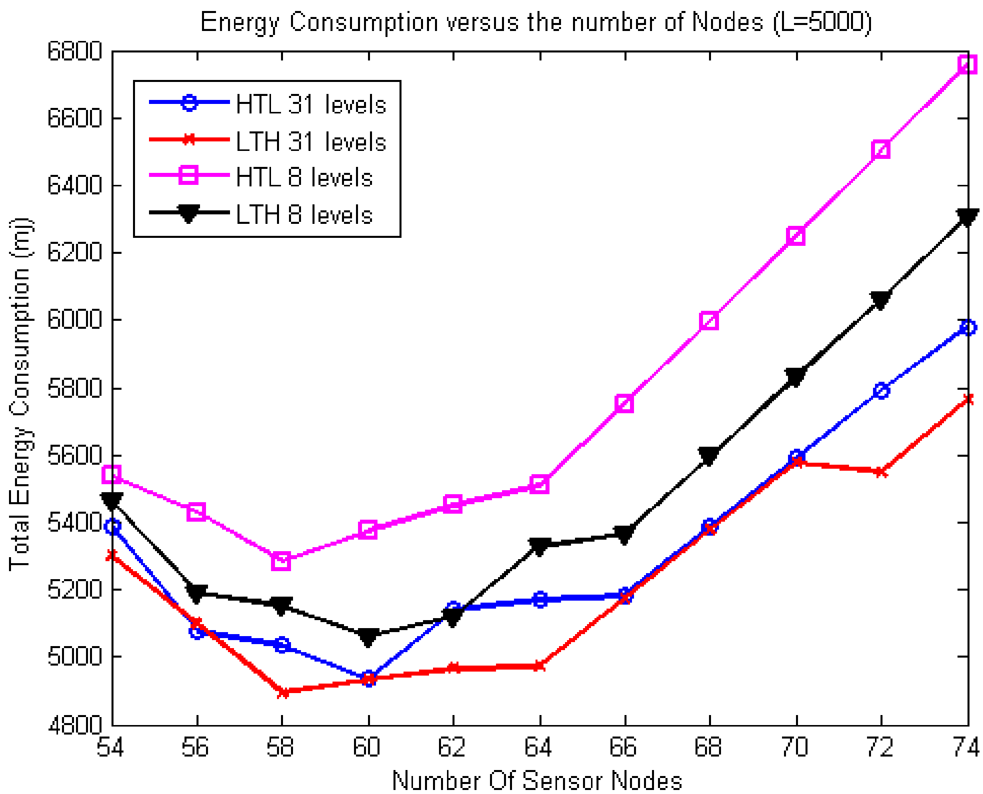

Figure 3.7: The total energy consumption using 31-power levels and 8-power levels when the length of the pipeline equal 5000 m

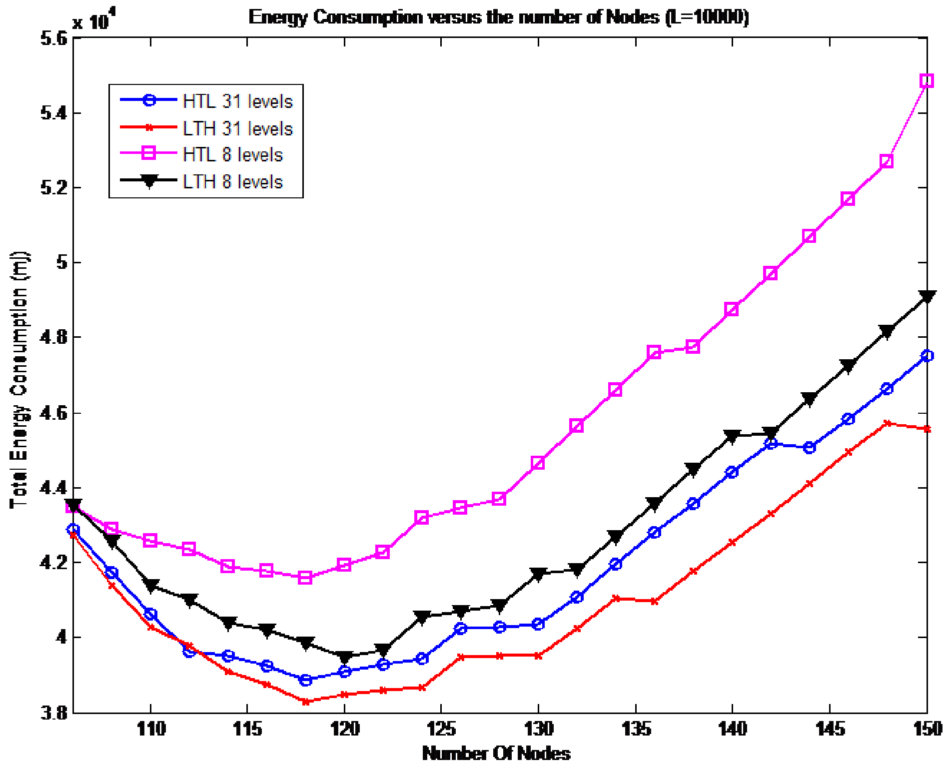

Figure 3.8: The total energy consumption using 31-power levels and 8-power levels when the length of the pipeline equal 10000 m

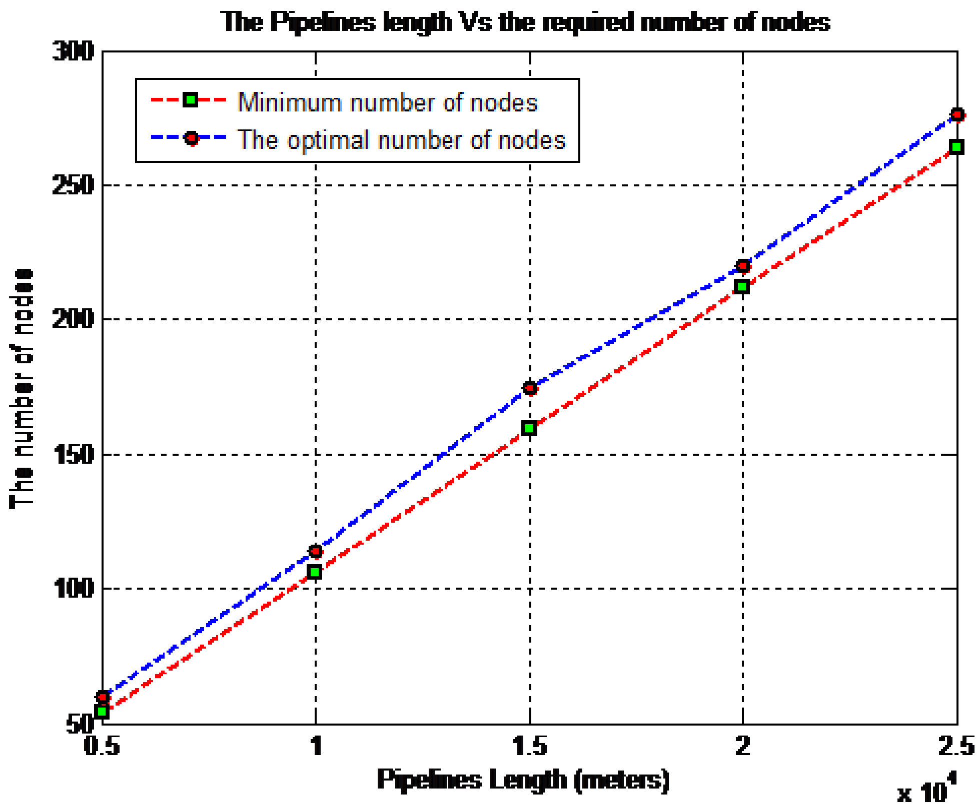

Figure 3.9: Pipelines length Vs the required number of sensor nodes

Overall, we can observe that the nodes distribution using the 31 alternative power levels outperforms the distribution using only the 8 commonly used power levels. However, in both scenarios, increasing the number of sensor nodes leads to significantly shorten the network lifetime (deploying more than 70 sensor nodes for L=5000 and 140 sensor nodes for L=10000) even with the use of the 31-power levels due to increasing the traffic loads which leads to higher power consumption. Overall, Fig. **??** illustrates the minimum and the optimal number of sensor nodes required to cover different pipelines length 5000, 10000, 15000, 20000, 25000 respectively. It can be observed that the maximum network lifetime is achieved when 1.1* n_{min} sensor nodes are deployed whatever is the length of the pipelines.

3.6 Real Experimentation

To validate the results obtained from the simulation in section 3.5, three different real experiments have been conducted with the small scenario. The pipelines length is assumed to be 100 m and initially, the same procedure explained in the previous section is implemented to find out the optimal number of sensor nodes and the expected lifetime in order to be compared with the results obtained from these experiments.

With the same parameters, the real experiments have been conducted as follows.

3.6.1 Methodology

In all experiments, TelosB sensor nodes are used and they are powered by using one pair of batteries (3V). Firstly, the performance of low to high and high to low are evaluated, the following software change scenarios are considered for TinyOS applications.

1. MultihopOsclliscope: it has been uploaded to all motes.

2. For network experiments, a testbed of 5 TelosB sensor nodes are deployed in a linear structure. But we set a different transmission power level for every node based on the output vector V resulting from algorithm 3.1 and algorithm 3.2. In all experiments, we gathered the data through multi-hop

wireless links. For the results, Java application also has been built to record the data received by the base station and save it to report file to be easily analyzed. [The sensor nodes have been deployed in the outdoor system in opened stadium with the length of 100 meters]. The built application has been uploaded to all sensor nodes. Firstly, we have deployed the sensor nodes based on algorithm 3.1 and the output power levels [27,4,3,1] have been elected to 5,4,3 and 2 sensor nodes respectively, as shown in Figure 3.11.

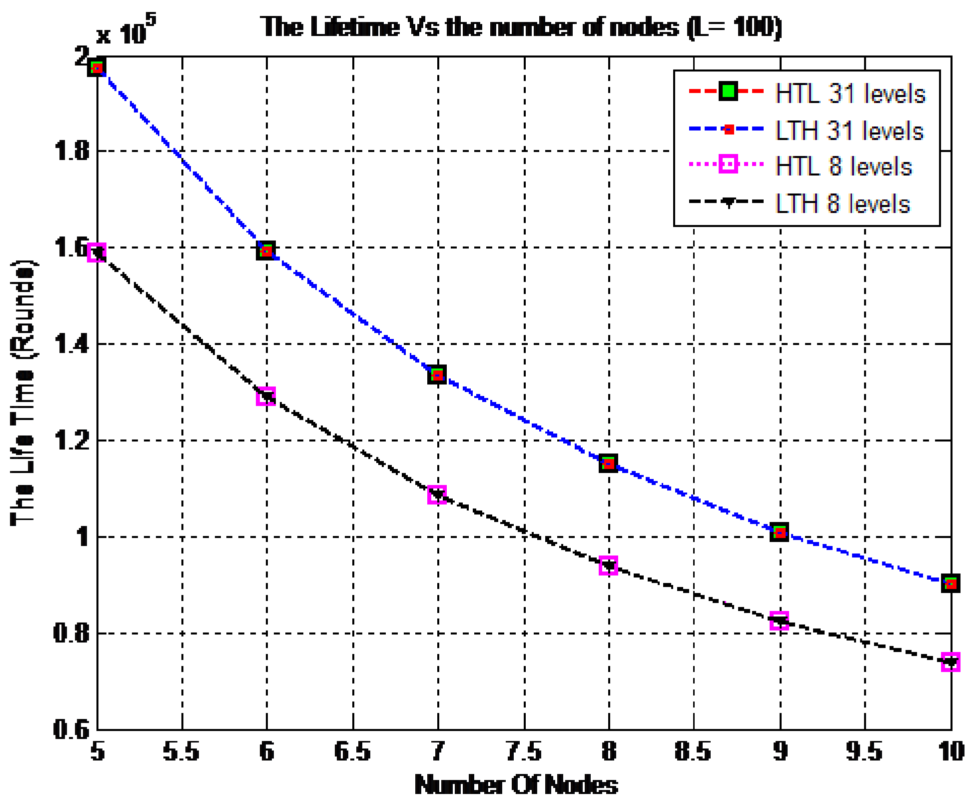

Figure 3.10: The lifetime using 8 power levels and using 31 power levels

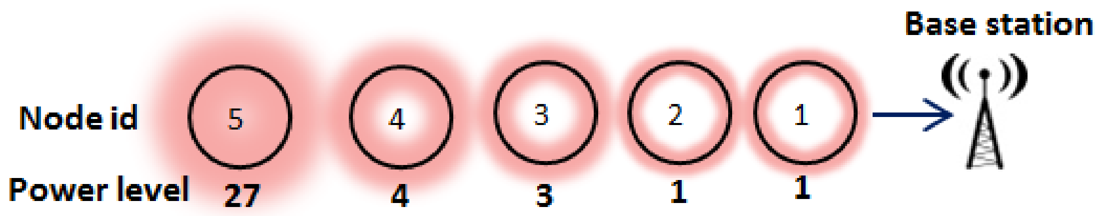

Figure 3.11: sensor nodes deployment based on low to high heuristic

Secondly, the deployment of the same sensor nodes has been achieved based on the algorithm 3.2 with replacing new batteries. The output power levels that have been used are 31,8,2,1 assigned to sensor nodes 5,4,3 as one for each and 2 sensor nodes to the same power level. Figure 3.12 illustrates the distribution of this scenario.

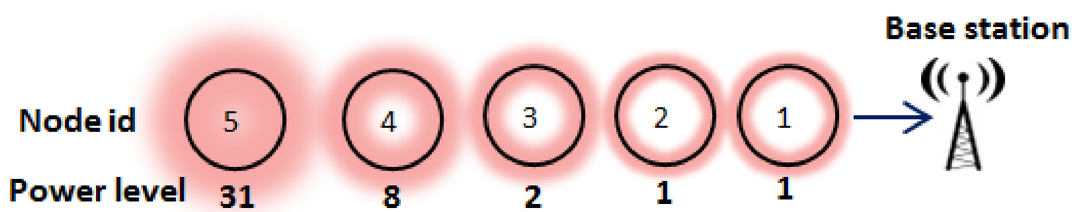

Figure 3.12: sensor nodes deployment based on high to low heuristic

3.6.2 Evaluation Results

To investigate the network lifetimes and total energy consumption of the two mentioned approaches and our proposed clustering approach, all experiments have been run until the first mote has drained out its energy. The simulation results point out that the lifetime in case of low to high or high to low equals 197139 rounds as shown in figure 3.10. The lifetime of the first experiment based on low to high distribution as depicted on 3.13 equals to 180274 rounds. It can be observed that the results given from this experiment are reasonable compared to the simulation result due to some additional power consumption (e.g., processing power, listening power) that is not considered when the simulation has been done. Similarity, the results of the second experiment based on high to low distribution show that the lifetime reaches to 179002 rounds, which are the lifetime of node id 1 as depicted figure 3.14. Also, it can be observed that the energy budget of the node 1 in both cases decreases significantly due to its heavier load coming from the other sensor nodes every second.

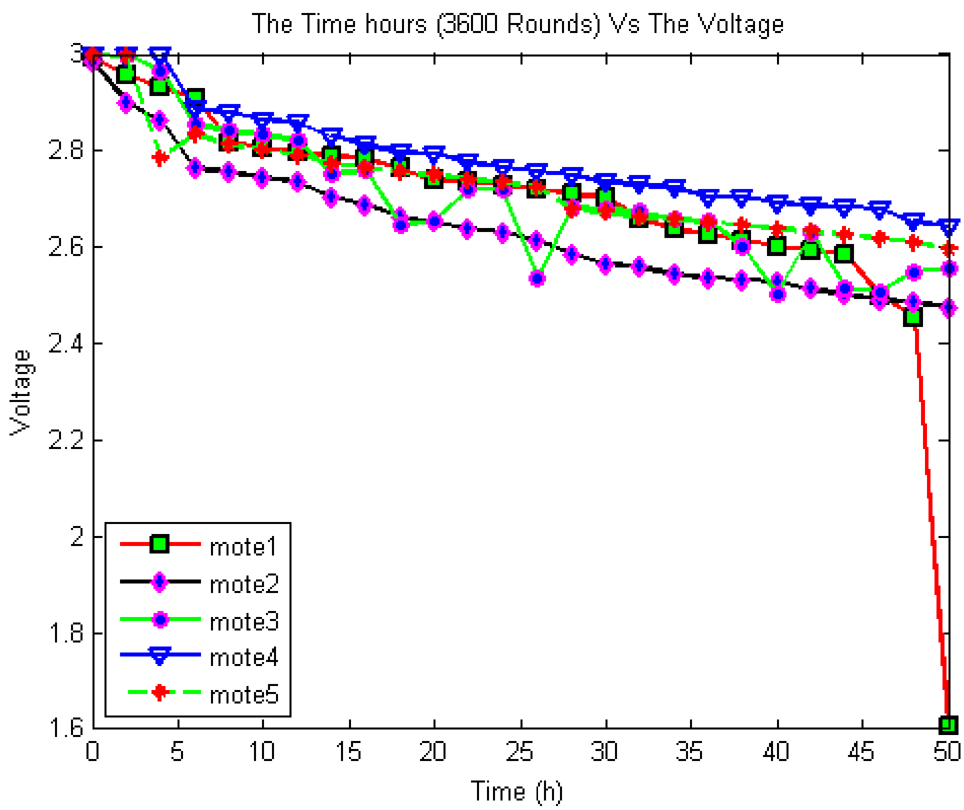

Figure 3.13: Low to high experiment (the voltage vs the time)

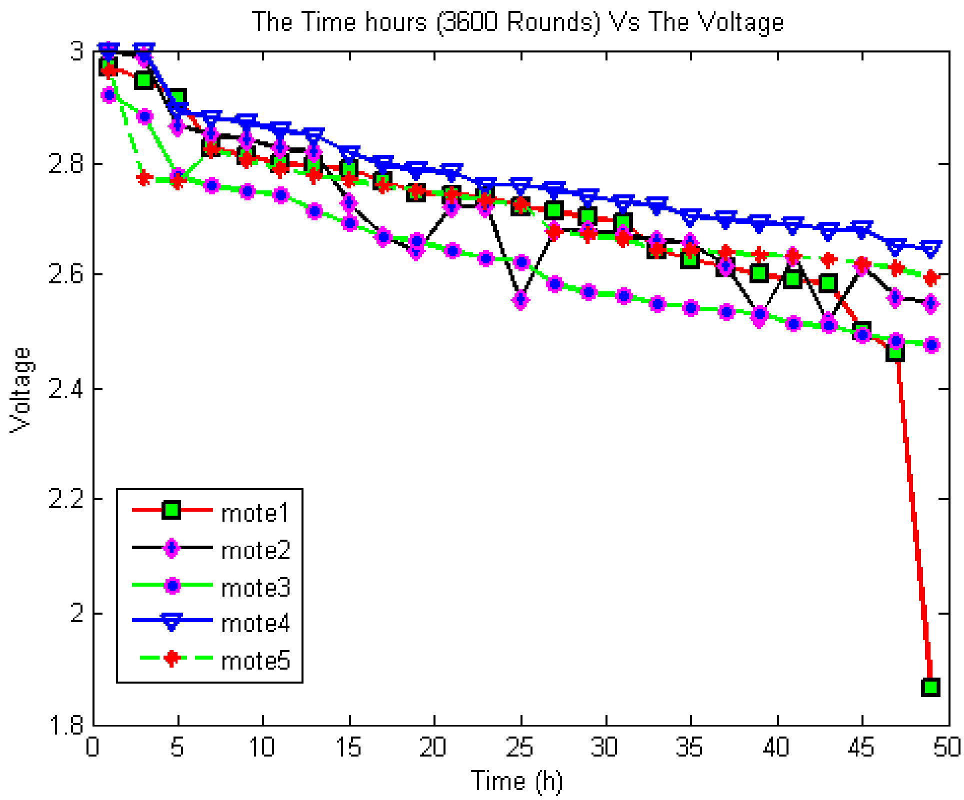

Figure 3.14: High to low experiment (the voltage vs the time)

3.7 Conclusion

In this chapter, the sensor placement problem in wireless sensor network used in pipelines monitoring system has been studied with the goal of maximizing the network lifetime. We have adopted a realistic CC2420 power model and it has been investigated under equal-power placement scheme where the energy is intended to be balanced. We have improved two greedy heuristics which are proposed in [8] based on real measurements of the transmission ranges of all 31 power levels. Real experiments have been carried out to measure the transmission ranges for all 31 power levels that are supported in this model. Extensive simulation and real experiments have been conducted to evaluate the performance of different placement approaches. The results reveal good improvements in the lifetime and total energy consumption. Also, the results obtained from the real experiments proved that using all 31 power levels improved the lifetime up to 23% compared to those using only the 8 power levels. The real experiments validate the obtained results with little differences due to some additional power consumption

CHAPTER 4

CLUSTERING-BASED NODE PLACEMENT APPROACH FOR WATER PIPELINES MONITORING

4.1 Introduction

In this chapter, we describe the first proposed dynamic clustering approach.

Clustering is predominantly beneficial techniques, especially, for applications that require a high scalability to tens and hundreds of sensor nodes due to the heavy loads on the sensor nodes nearest to the monitoring unit. In this context, the scalability means the need for load balancing, efficient resource utilization, and reliable data aggregation.

Taking the advantages of the clustering techniques, this chapter investigates the effects of the nodes placement on the lifetime and the energy consumption with the aim of maximizing it. We have proposed a novel clustering approach called equally-distance Equally Members approach (EDEM). This approach, prominently gathers the sensor nodes based on their power levels to balance the loads among the sensor nodes and considers the required fidelity. In this approach, all clusters have the same number of nodes.

The rest of this chapter is organized as follows: in section 4.2 the problem statement and system-level assumptions are discussed while the proposed approach is clarified in detail in section 4.3. The simulation experiments and results analyzing are discussed in section 4.4 while the real experiments that validate our approach are introduced in section 4.5. we conclude this work in section 4.6.

4.2 Problem Statement and System-level Assumptions

We consider a WSN comprised of multiple sensors placed on-pipes and ended with a BS as shown in figure 4.1. The SNs are deployed along the pipelines in pre-selected sites. These SNs oversee data acquisition then they report periodically to the BS. All SNs play an important role for forwarding this data between the reported SN and the BS using multi-hop forwarding scheme. The data to be forwarded to the base station should be carried by the nodes located between the sender SN and the BS via multi-hop routes. This is apt to extremely waste the energy of the sensor nodes placed nearest to the BS due to highly asymmetric loads on these nodes. Finally, the BS after processing the received data judges whether a problem has already occurred or not.

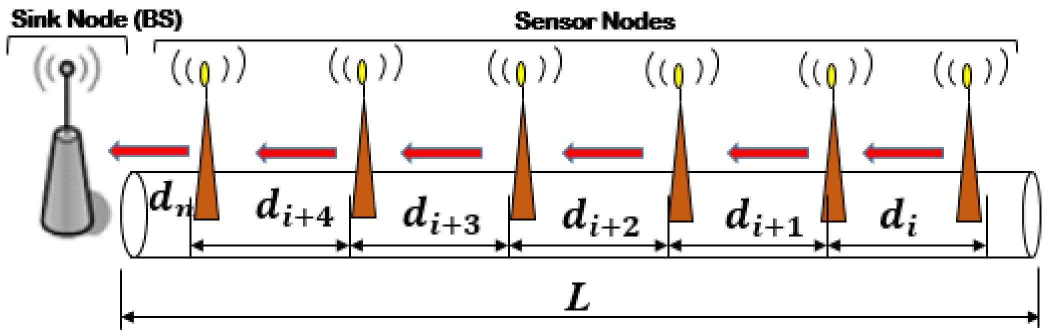

Figure 4.1: Architecture of the proposed pipelines monitoring sensor network

The following enumerates the key system model assumptions:

1. Each sensor node is responsible for performing a periodic inspection based on its sensing range.

2. All sensor nodes are homogeneous, i.e., have the same power model, communication capabilities, energy supply, etc.

3. Each SN delivers its packet to its neighbor towards the BS.

4. The distances between the adjacent SNs are equal due to the need for a reliable communication because in the greedy heuristics the receiver cannot acknowledge the sender as depicted in figure 4.2.

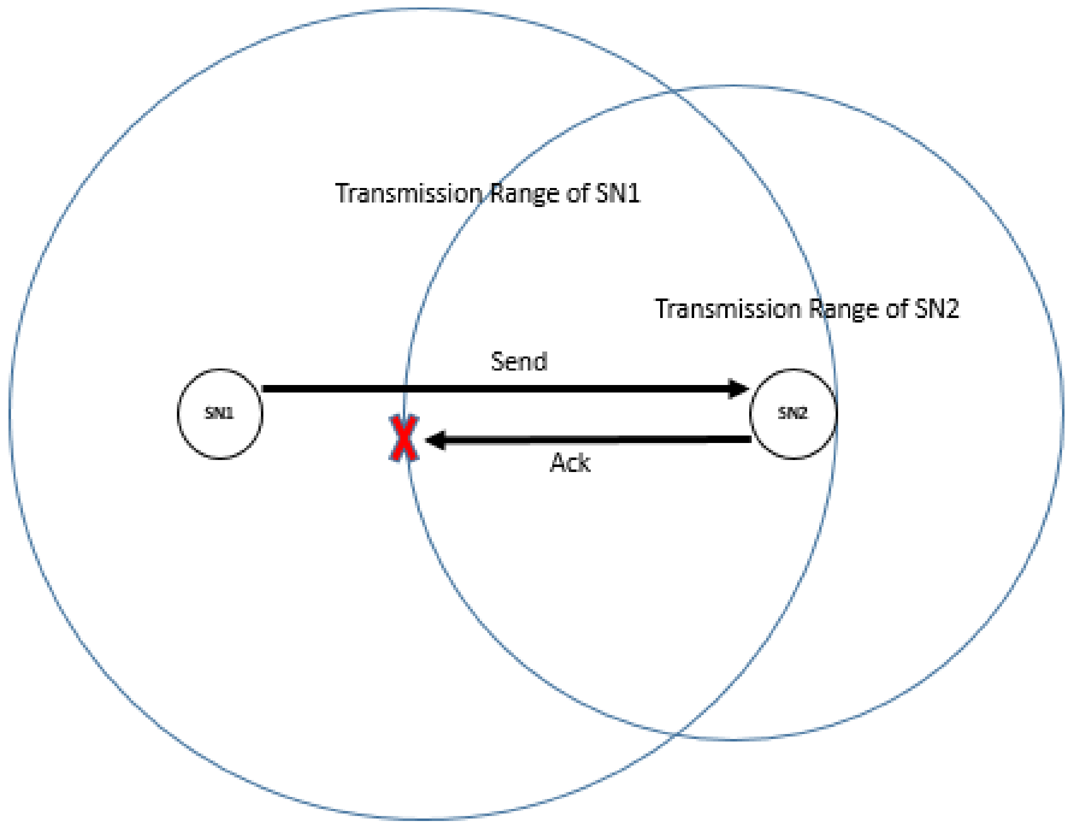

Figure 4.2: The limitation of greedy heuristics due to the inability of the receiver to acknowledge the sender

5. The BS receives the data from all sensor nodes and performs the required actions.

4.2.1 System Model

Denote L the length of the pipelines ended by the monitoring unit (i.e. Base Station) that aggregates and summarizes the data. Let n be the sensor nodes along these pipelines and let i denotes to specific sensor node where $1 \leq i \leq n$. Lets m be the number of power levels (i.e. m=31 for TelosB, MicaZ) and each sensor node has a transmission power P_j with a communication range R_j where $j = 1, 2, 3, \ldots, m$. For instance, to transmit the data at power level j, the required transmission power is P_j. Any SN can be set to a different power level thus, it can communicate within different transmission ranges.

Our goal is to determine nodes that will serve as cluster heads such that it reduces the total power consumption among the whole network. Each sensor node has to be assigned to only one cluster c_r, where $1 \leq r \leq NCH;$, NCH is the number of clusters ($NCH \leq n$). Also, each sensor node can completely communicate with its cluster head (via a single or multiple hops). The aim is to balance the energy consumed by all SNs as much as possible.

4.3 Equally-Distance Equally Members Approach

To avoid the shortcomings of the greedy heuristics approaches, the length of the pipelines aredivided into equal small segments and each segment should not exceed the maximum transmission range (e.g. 95m if TelosB mote is used.)

Each segment represents a cluster and this cluster has three sensor nodes and the distance between the adjacent sensor node must be less than or equal to 32m to acquire the required fidelity because the signal is acoustic and it is essential to place more than sensor node to detect the leak signals in order to obtain the required fidelity. The fidelity here means the leak signals should be heard by more than sensor node because if the failure in detecting the problem occurs on one side, another sensor can detect and report to the BS. Figure 4.3 illustrates such case.

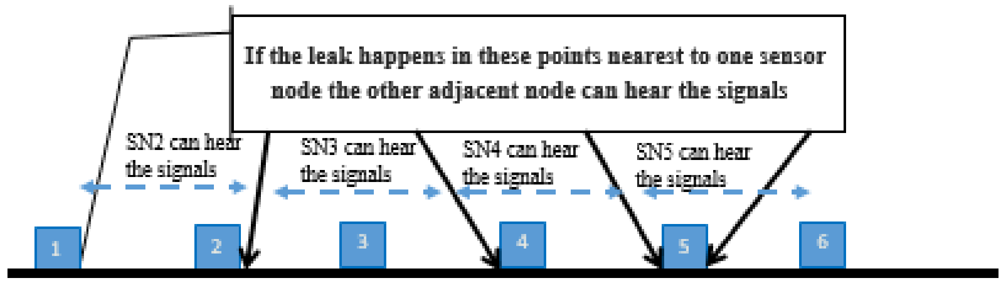

Figure 4.3: The required level of fidelity to capture the leak signals by more than sensor node

$$d_{fid} \leq \frac{R_{max}}{n_{min}}$$

Where d_{fid} is the optimal distance to assure the fidelity R_{max} is the maximum transmission range and n_{min} the minimum number of sensor nodes that achieves to assure this fidelity.

Furthermore, all clusters have the same number of sensor nodes and the cluster head is responsible for sending the loads from its members to the next cluster head and so on to reach the base station. In each cluster, the sensor nodes other than the cluster head transmit and forward the packets only among the same cluster leading to reduce the energy consumption. Firstly, we simulate a small scenario when the pipelines are 950 m and the number of nodes is 30 to know the effect of the clustering in the power consumption. However, this scenario is performed without dynamic clustering. The last sensor node in each cluster works as a CH all the time leading to more power consumed by this node while the sensor nodes other than the CH still retain a large amount of energy as depicted in Fig 4.4.

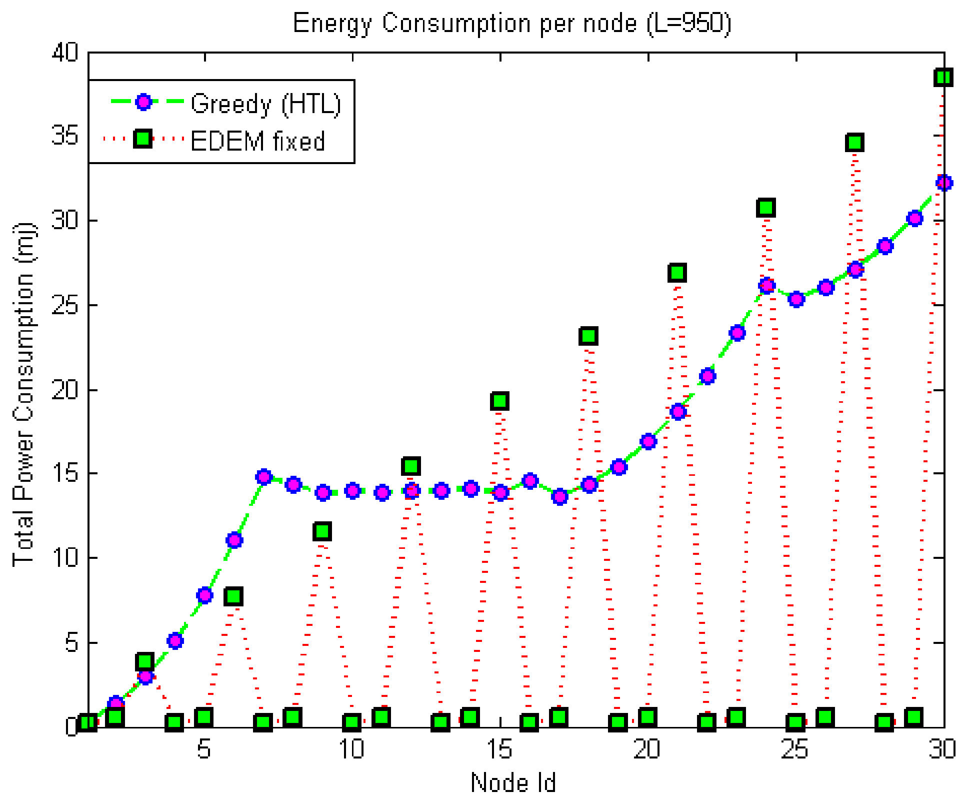

Figure 4.4: The clustering approach with fixed cluster head vs the greedy (HTL) approach when the pipelines are950 and the number of sensors is 30

Therefor, in each cluster, the leader (cluster head) is elected periodically to balance the energy consumption among the same cluster so every sensor node serves as a CH. Fig 4.5 illustrates the first step of electing the CH when the last sensor node in each cluster is the leader. This sensor node sends the packet with the maximum transmission power to deliver the data to the forwarding CH towards the base station. Similarly, Figure 4.6 explains this mechanism when the middle sensor node in each cluster is the leader. In addition, Figure 4.7 describes this procedure when the leader is the first sensor node in each cluster. The next two algorithms describe the mechanism of this approach. We assume that all sensor nodes are synchronized.

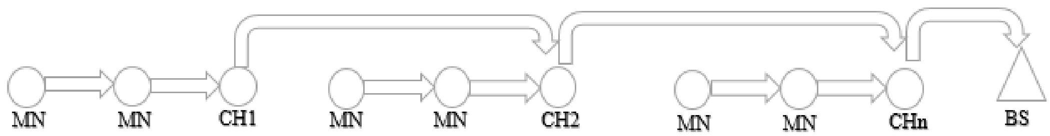

Figure 4.5: The initial case where the cluster head is the last node in each cluster

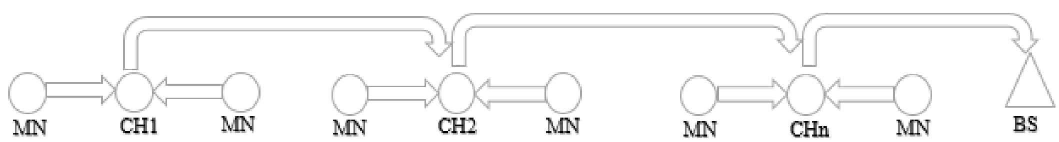

Figure 4.6: The second case where the cluster head is the middle node in each cluster

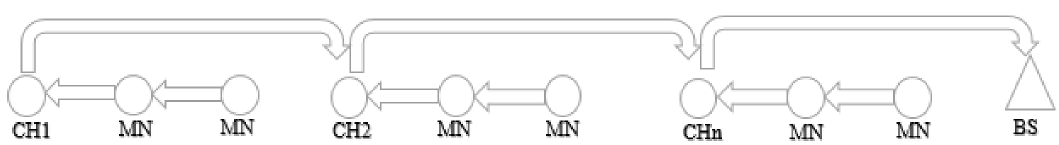

Figure 4.7: The third case where the cluster head is the first node in each cluster

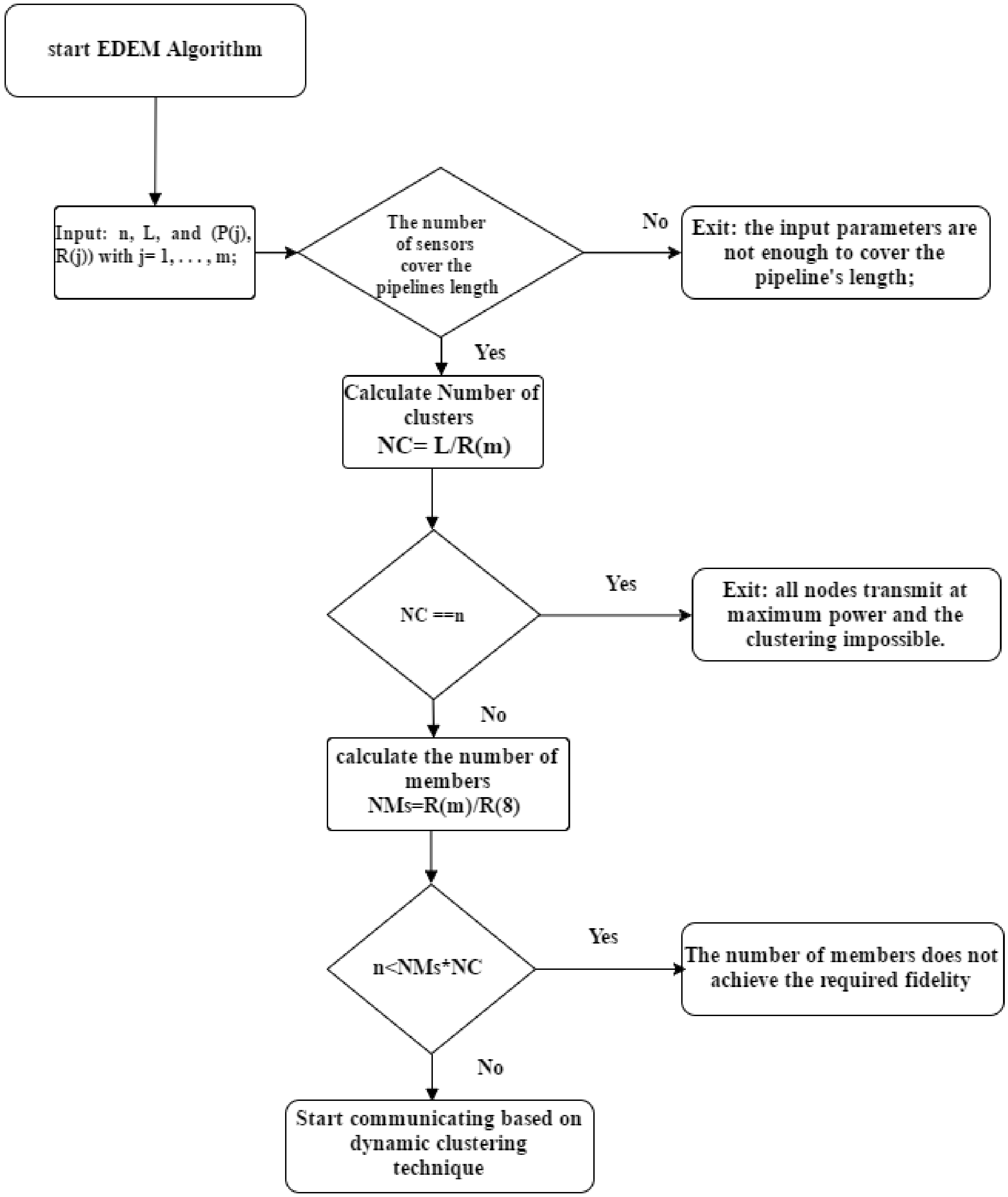

Figure 4.8: Equally-Distance Equally Members algorithm (Flow chart)

Table 4.1: EDEM members algorithm

Input: n, L, and $(P_j,\ R_j)$ with j = 1, . . ., m; //m=31

$if\ (n.\ R_m <\ L)\ then$

Exit: the input parameters are not enough to cover the pipelines length;

end if

calculate number of clusters $NC = \frac{L}{R_m}$ //the number of clusters

If (NC==n)

Exit: all nodes transmit at maximum power and the clustering impossible.

End if

$NMs = round(\frac{R_m}{R_8})$ //// number of members

$If\ (n < NMs * NC)$ to obtain the required accuracy (the range of PL8 is 32)

Exit: The number of members do not achieve the required fidelity

End if

Start communicating based on dynamic EDEM Algorithm

Table 4.2: EDEM mechanism algorithm

1 Start assign the last SN in each cluster to be in charge as a CH and start announcing

2 set i=1

3 For all SNs along the pipelines $SN_i \leq n$

4 compute the $Threshold_{index} = \frac{E_{budget}}{\alpha}$;

5 if SN_i is CH

6 Set the transmission power to P^{max}

7 end if

8 if SN_i is normal node // Normal sensor node

9 Set the transmission power to P^8

10 end if

11 check the energy status of All CHs

12 if ($E_{budget} \leq Threshold_{index}$)

13 send advertisement 'I am NOT a CH'

14 in all cluster select the other SNs to be a CH

15 end if

16 end for

4.3.1 Algorithm Description

Firstly, this algorithms test (steps 2-4) if the number of sensors n is not enough to cover the intended pipelines length L, this algorithm will fail and exit. Otherwise, the sensor nodes are grouped into clusters based on maximum transmission range R_m (step 5). Thus, the length of each cluster equals to R_m (i.e. $R_m = 95$ In CC2420 power model). In addition, each cluster selects one sensor node to be a leader and in charge of forwarding the internal and incoming packets. This CH transmits at its maximum transmission power. But to start the clustering, the number of SNs should be completely enough (line 6-8). In order to select the member SNs, they should be selected carefully to obtain the optimal number of members that achieve the minimum required fidelity (steps 9-12). Line 13 is the beginning of clustering mechanism which is explained in the second algorithm. Firstly, the last SN in each cluster is selected as a CH (step 1). The other SNs is set to transmission power of level 8. The steps from 3 to 16 is the process of the dynamic clustering based on the energy budget (step 11 to 12) which should be periodically checked to know the time for changing the CHs (step 13 and 14).

4.3.2 The Power Consumption Model

The total power consumption of each cluster is computed by calculating the inner power consumption consumed by cluster members and the power consumption consumed by the cluster head itself. It can be modeled as

$$P_{total} = \ intra\ power\ consumption\ +\ inter\ cluster\ head\ power\ consumption$$

. The intra-power consumption is the energy that is consumed by the sensor nodes in the same cluster while the inter-power consumption is the energy consumed by the cluster head of the cluster. Firstly, the intra power consumption EC_i can be calculated as

$$EC_i = \sum_{j=1}^{k-1} j.P_T.t + (j-1).P_R.t \tag{4.1}$$

which EC_i is the energy consumption of sensor nodes in cluster i and k is the number of these sensors in each cluster which is evenly adopted in this approach. Also, P_T is the required transmission power for one packet, P_R is the required receiving power for one packet and t is the required time for transmitting or receiving a signal packet.

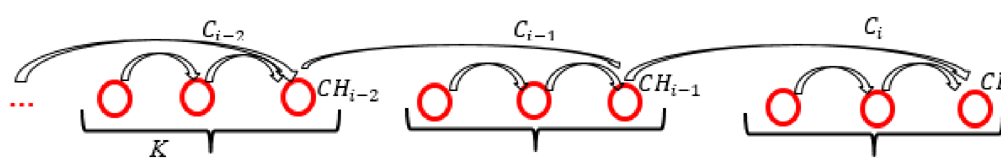

Figure 4.9: The intra power consumption and the inter cluster head power consumption model when the CH send the packets from its cluster and from preceding clusters

Secondly, the inter-power consumption of the Cluster Head CH_i can be calculated as

$$ECH_i = (i.k).P_C.t + (i.k-1).P_R.t \tag{4.2}$$

From the Eq 4.2, the total power consumption of each cluster can be modeled as:

$$P_{total_i} = EC_i + ECH_i \tag{4.3}$$

Based on equation 4.3 the lifetime of each cluster can be calculated as:

$$LT_{c_i} = \frac{k.E_{budget}}{P_{total_i}} \tag{4.4}$$

4.4 EDEM Evaluation

We have conducted extensive simulation experiments examining the effectiveness of EDEM approach.

MATLAB has been used to simulate the proposed EDEM approach with different pipelines length. The adopted lengths start from 950 up to 9500 meters. The performance metrics used in this study are:

1. Total power consumption: this metric measures the total energy of each sensor nodes as in equation 3.6 for the greedy scheme and as in equations 4.1 and 4.2 for EDEM clustering scheme. This metric also shows how effective is the proposed solution in term of how much of the energy is conserved.

2. Network lifetime: this metric measures the estimated lifetime of each sensor nodes based on the equation 3.7 for the greedy scheme and based on equations 4.4 for EDEM clustering scheme. This metric Also determines the lifetime of the whole network. In addition, this metric shows how the ability of the proposed EDEM clustering solution in term of how much of the network lifetime is expanded.

3. Total packets: this metric counts the number of packets that are forwarded

in each round throughout the network. This metric shows how ability of the proposed EDEM clustering solution in term of how much of the forwarded packets.

All the previous metrics can be used to explicitly judge what the node placement approach that should be adopted and why.

We have compared our proposed approach with the greedy approach which has been adopted in many previous studies [12], [7], [21], [8] as mentioned in the preceding chapter. The proposed clustering approach is explained in detail in section 4.3. While We describe briefly the greedy approach as follows:

- Greedy approach: This approach has widely studied in [12], [7], [21], [8]. In this approach, the density of the deployed sensor nodes increases as we get closer to the BS. Also, the farthest sensor nodes send at maximum transmission power and the closest SNs send by minimum transmission power.

Parameter	Value
Simulation Tool	MATLAB
The pipelines length	950, 1900, 3800, 470, 9500 meters
The number of sensors sensor nodes	30, 60, 120, 150, 300
Battery capacity	2600 mAh
Battery Voltage	3 V
The time of sending/receiving one packet t	1 second
Receiving power R_x	0.0564 Watt
The transmission Power P_T(member node)	0.0297 Watt
The transmission Power P_C(Cluster Head)	0.0510 Watt

Table 4.3: Simulation parameters

4.4.1 Results and Discussion

The performance evaluation of the proposed node placement approach is considered under different scenarios. Firstly, for the sensor nodes distribution, the sensor nodes are deployed based on the output vector V of the greedy approach as in algorithms 3.1, 3.2. While for the EDEM approach, we have assigned the power level 31 for all cluster heads while the distance between all adjacent sensor nodes is 32m which a transmission range of power level 8. For both approaches, we have used the same number of nodes, but the distances between the sensor nodes are based on the transmission ranges of the assigned power levels of V.

For the EDEM approach, the CHs are changed periodically based on the α value as figure 4.10 illustrates.The tested scenario is 950 m when the α varies from 0.01 up to 0.25. We can observe that the lifetime increased as the α value decreased so we adopt the minimum α in all coming tested scenarios.

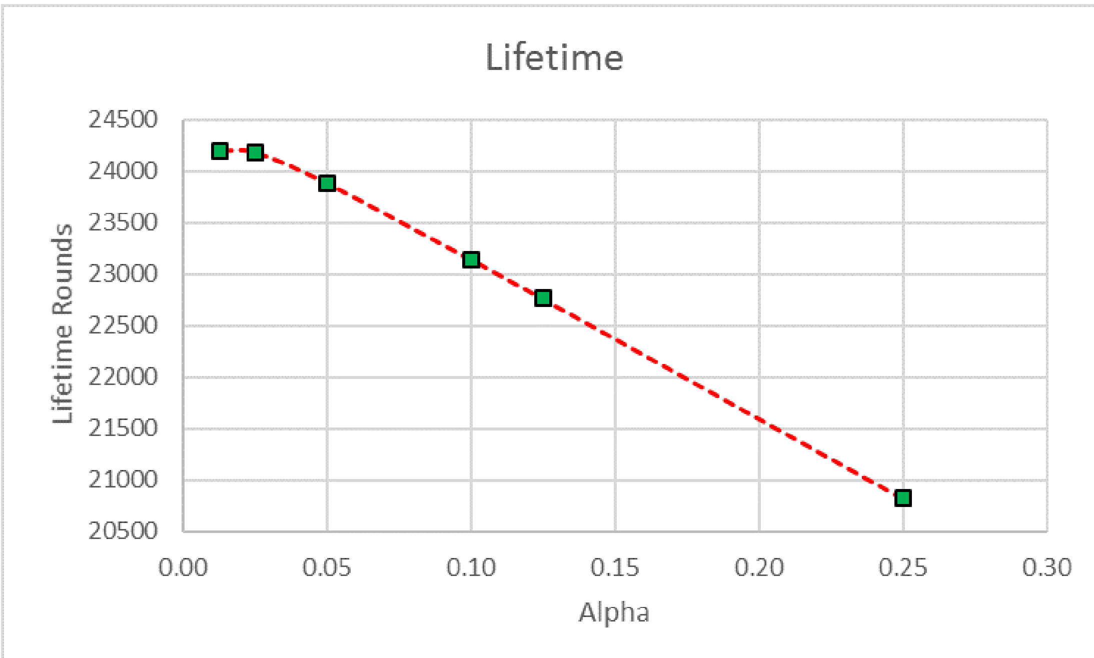

Figure 4.10: The network lifetime when the length of the pipeline is 950 m and the number of sensors is 30 and different α

Figure 4.11 shows the lifetime of the network using both approaches. It can be observed that the lifetime of our approach outperforms the greedy approach in all tested scenarios because the loads decrease along the network and only specific sensor nodes cooperatively carry out the packets towards the BS. The increasing ratio ranges from 56% when the length of the pipeline is 950 up to 62% when the length of the pipeline is 9500. In contrast, increasing the length of pipelines in both approaches yields to significantly shorten the network lifetime.

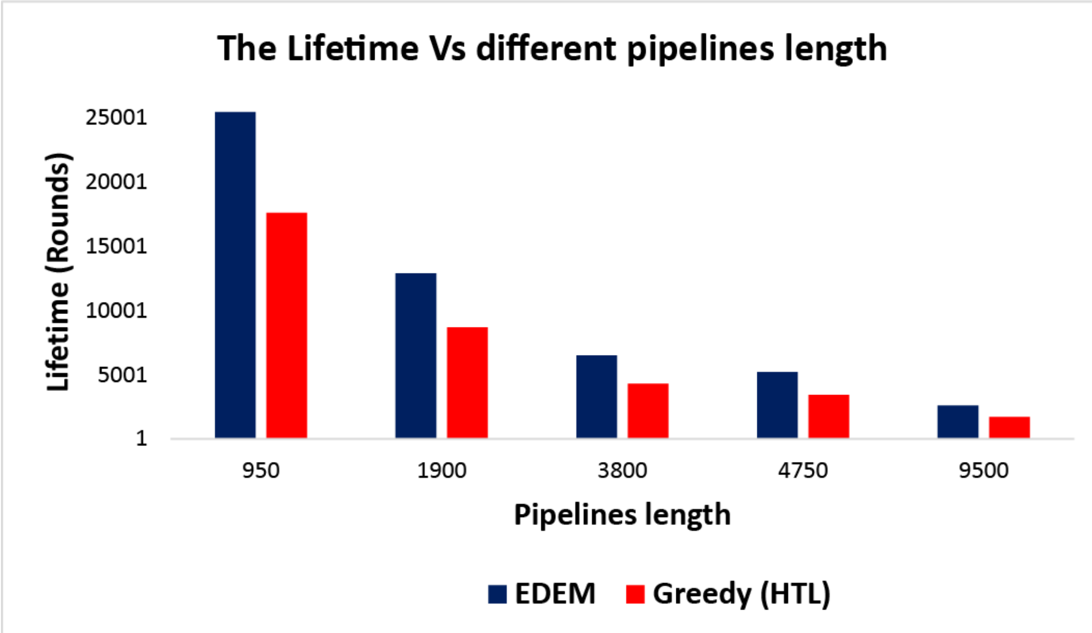

Figure 4.11: The lifetime of the network when the length of the pipeline is 950, 1900, 3800, 4750 and 9500 meters

In addition, figure 4.12 illustrates the power consumption in all tested scenarios. Our proposed approach can conserve the energy along the whole network because the main advantage of our approach is two features sharing the loads among all cluster nodes and balancing the power consumption. On the other hand, in the greedy approach, the last sensor node is in charge all the time to deliver all coming packets to the BS. The amount of energy savings can reach to 300% when $L = 950$ and up to more than 500% when $L = 9500$. This big difference is affected by the procedure of our approach leading to reduce the number of forwarded packets which in turn reduce significantly the required transmission and reception power.

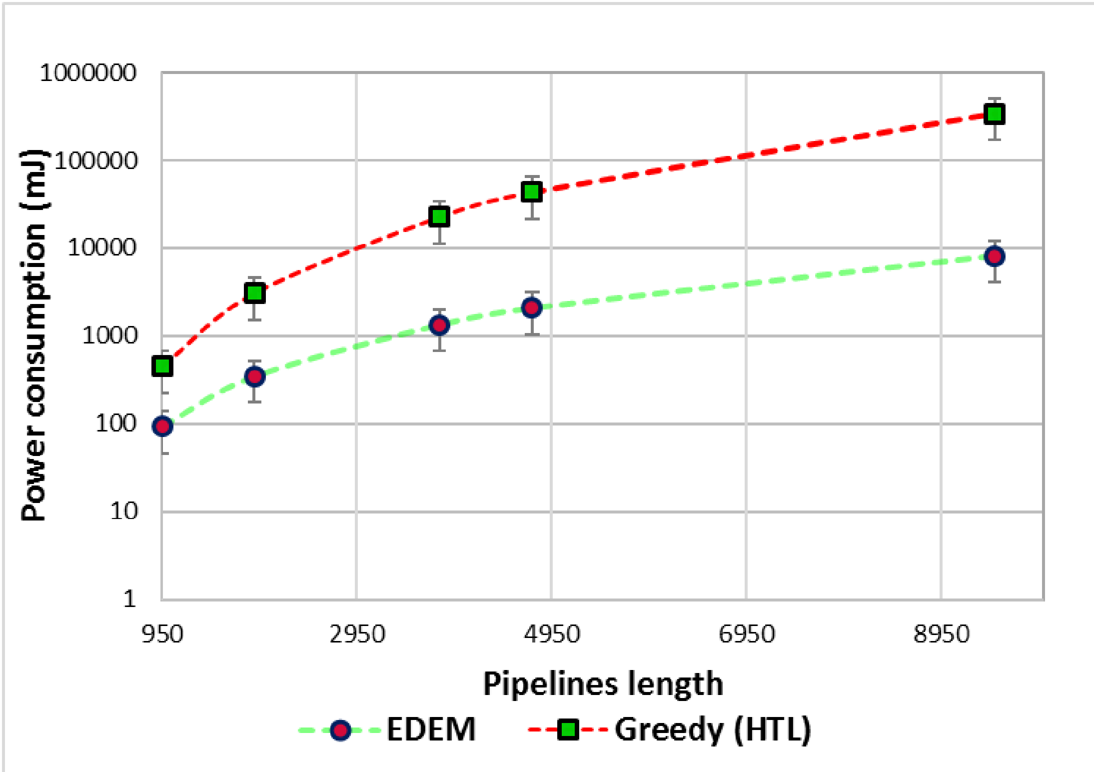

Figure 4.12: The power consumption when the length of the pipeline is 950, 1900, 3800, 4750 and 9500 meters

Moreover, we can notice that in Figure 4.13, the amount of the sent and forwarded packets which dramatically decreased when our approach is applied because of the number of hops that the packets should pass decrease significantly. For greedy heuristic, the number of hops of the packet sent by SN_i is $n - i$ while in EDEM approach, these hops equal to a number of clusters NC. In details, the

$$Num\ of\ hops\ node(i,j) = \begin{cases} NC - j & if\ the\ sender\ is\ CH \\ (NC - j) + (k - i) & if\ the\ sender\ is\ a\ normal\ node. \end{cases}$$

where j is the cluster id and k is number of members

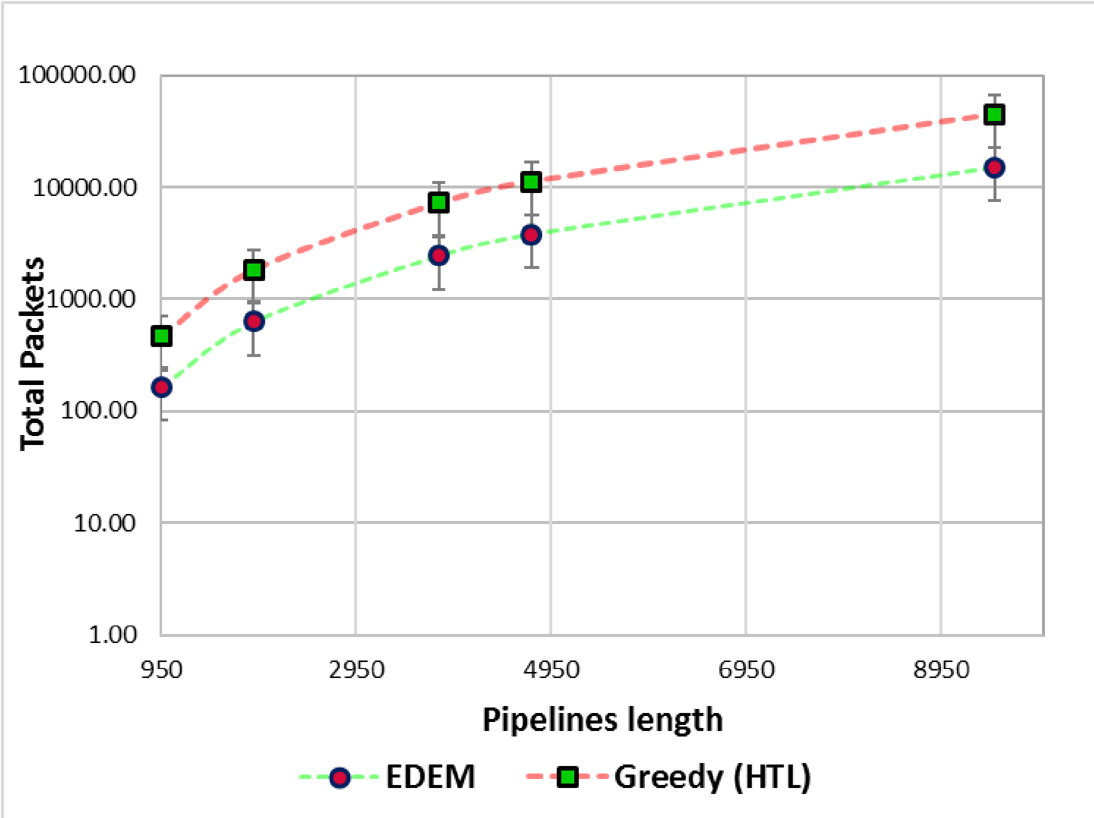

Figure 4.13: The total sent and forwarded packets when the pipelines length is 950, 1900, 3800, 4750 and 9500 meters

From the previous results, we can observe the outstanding performance of the proposed dynamic clustering (EDEM) approach compared to the performance of the greedy approach.

4.5 Experimental Study

In order to validate the simulation results, the two approaches deployments are implemented using real hardware devices in the outdoor environment: Greedy algorithm, and EDEM clustering algorithm.

4.5.1 Methodology

We have carried out two different experiments (i.e. one for each approach) using real motes hardware. Each experiment has been repeated five times to acquire more reliable results. The aim is to determine the impact of the studied node placement approaches on the sensor battery lifetime.

Our set of experimental studies has been implemented using TelosB motes. These motes have been supplied by AA batteries to enable us pointing out varied observations.

The experimental setup consists of the following parts:

- 30 TelosB motes are deployed along the 950 meters pipelines length.
- 01 mote is connected to the gateway as a sink node to receive data from the other motes. Then it forwards the data to the PC.

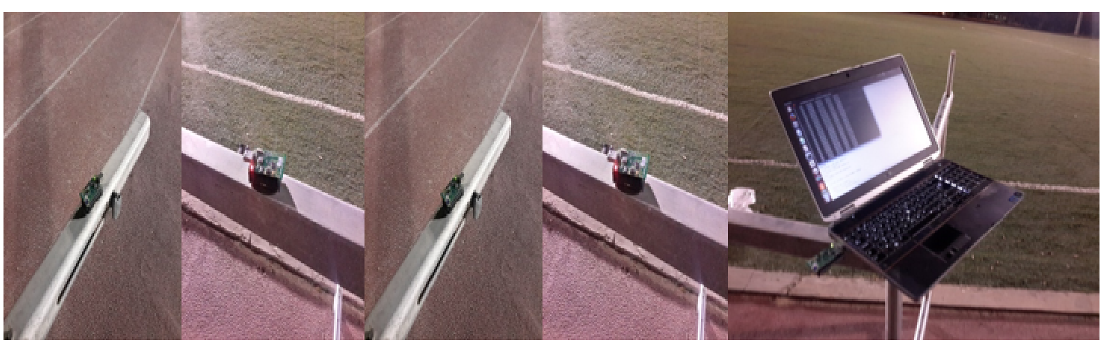

Figure 4.14: An example of the real implementation using TelosB motes. A) One mote is connected to the laptop. B) The other nodes are deployed in the outdoor environment.

- Gateway: Using serial dump tool to get data from the sink node's serial port and a terminal client running to capture these data.

- ContikiOS: used to program the motes and it is described in the next section.

Firstly, these motes have been deployed based on the greedy output vector V which identifies the transmission power level of each mote as illustrated in table 4.4. The distances between the motes are adopted based on the transmission range of each power level (i.e. measured in chapter 3 using real experiments).

Table 4.4: Power level assignment of greedy approach experiment

Power level	31	24	20	15	11	8	5	4	3	2	1
The number of motes	6	1	1	1	1	1	1	2	7	5	4

Secondly, for the EDEM experiment, the same components are used, but the deployment of the motes is achieved based on our proposed algorithm which is explained on section 4.3. The distance between the adjacent nodes is equal to 32m. Each cluster covers the distance equals to 95m.

For power consumption, we use Contiki's internal power profiling [52]. Contiki has a built-in power profiling module that measures the uptime of various components (i.e. it can be used to estimate the radio duty cycle). For every sensor node in the network, the *Energest* module has been combined with the uploaded code to track the power consumption and append the readings to the packets sent to the BS.

The following steps illustrate the procedure to estimate the energy consumption:

1. Every SN collects its readings and reports to the BS every five minutes (300 seconds).

2. The time of sending and forwarding all packets in one round is called a cycle.

3. For every reading of the TX, RX, LPM and CPU, we compute the energy consumption of each mode based on its current consumption (i.e. The current of TX at level 31 is 17.4 mA). The equation 4.6 is used to calculate each part.

4. The total energy consumption of each cycle is calculated as follows:

$$Energest_{value}\ percycle = current\ Energest_{value} - previous\ Energest_{value}. \tag{4.5}$$

Where $Energest_{value}$ is the times that the mote spends in this state

$$Energy\ consumption(mW) = \frac{Energest_{value} * current * Voltage}{RTIMER_{SECOND} * Runtime} \tag{4.6}$$

Where the $RTIMER_{SECOND}$ is the number of ticks per second.

$$P_{total} = P_{Tx} + P_{RX} + P_{LPM} + P_{CPU} \tag{4.7}$$

5. To calculate the overall energy consumption, calculate P_{total} for all cycles.

As illustrated in table 4.5.1 , we have used TelosB mote with current in active mode is 1.8 mA, sleep mode is 5.1 uA, TX mode is variable based on assigned power level, and the RX is 18.8 mA. Also, the voltage is 3.V.

ContikiOs enables us to track the time of how much every mode is in active state. All_Tx, for example, is the total TX time from the beginning of sensor operation, in the form of many ticks. So, to estimate the energy consumption in a duration of time, we just consider the power incurred during that time by subtracting the current ALL_TX to the previous ALL_TX because the *Energest* value is always incremented and never reset to zero.

Table 4.5: Real Experiment Parameters [1]

Parameter	Value
ContikiOs Ver	2.7
Number of sensor nodes	30
The pipelines length	950 meters
Tx current consumption	variable
Rx current consumption	18.8 mA
CPU current consumption	1.8 mA
LPM current consumption	5.1 uA
Voltage	3 V
nominal capacity	2600 mAh

4.5.2 Contiki OS

Contiki operating system is first created by Adam Dunkels in 2002, and it is now maintained by the Swedish Institute of Computer Science (SICS) in Sweden.

The Contiki community is one of the largest and most active IoT communities now. Supported by Texas Instrument (TI), Atmel, Seminude, Cisco and many other companies and organizations. The Contiki OS is designed particularly for low-power wireless IoT devices with constrained memory and resources. The minimum memory required for a complete IP-supported Contiki OS could be less than 10 kilobytes, with less than 30 kilobytes ROM required [52]. Contiki provides a light-weight programming model based on protothreads, achieving low memory overhead of each process. Protothreads absorbs the features of both multi-threading and event-driven programming [52]. Contiki manages a real-time clock and an event clock. System level operation and a low layer of network operation are scheduled and triggered by the real-time clock. Event clock, on the other hand, serves the upper layer processes and application defined processes that do not require high accuracy. Besides multi-tasking, Contiki provides full stack support for different networking mechanisms, including uIP-based TCP/IP stack, Rime stack, and the uIPv6 stack.

4.5.3 Experimental Results and Discussion

The performance of the two approaches has been investigated using different setups to explore the effect of using real sensor nodes in outdoor environments. First, we show the effect of greedy algorithm placement on lifetime and the total energy consumption.

Figure 4.15 shows the lifetime of each node under the greedy approach. As we can notice the lifetime here is dictated by the lifetime of the node 2, nearest to the BS, because of its responsibility to forward all packets to the BS all the time leading to depleting its energy quickly. Also, this figure illustrates the lifetime of the other two nodes beside this node with the same power level. In addition, we can observe that the lifetime of the nodes decreases based on the distance to the BS.

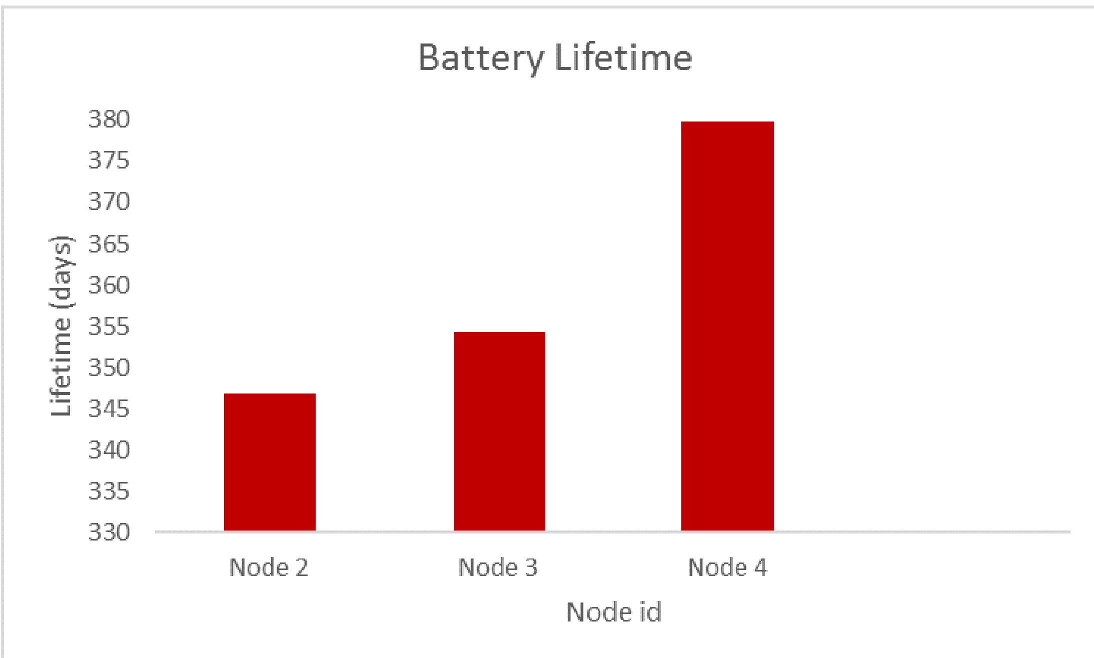

Figure 4.15: The lifetime of the last three sensor nodes besides the BS (Greedy Approach) when the length of the pipeline is 950m and the number of the deployed sensors is 30.

In contrast, figure 4.16 shows the lifetime comparison between the two studied approaches. It can be concluded that the proposed approach can increase the lifetime by 50%. This enhancement in the lifetime because of the dynamic clustering and sharing the loads. The other normal sensor nodes just pass the packets within the same cluster towards their CH.

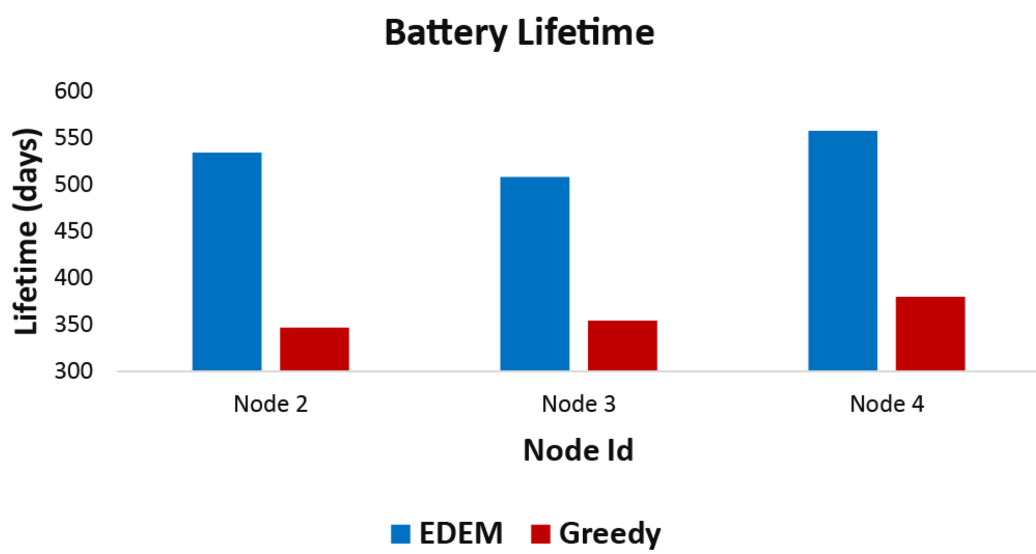

Figure 4.16: The lifetime of the greedy approach and EDEM approach when the length of the pipeline is 950m and the number of the deployed sensors is 30

Power Consumption Analysis

The power consumption test mainly focuses on the power consumed on each transaction. In figure 4.17, the power consumption of each transaction in case of greedy approach deployment is depicted. We can observe that the last node which is node 2 consumes the highest power all the time because it should forward all packets coming from the whole network. Also, it can be noticed that the power consumption is gradually decreased as these nodes become far away from the BS.

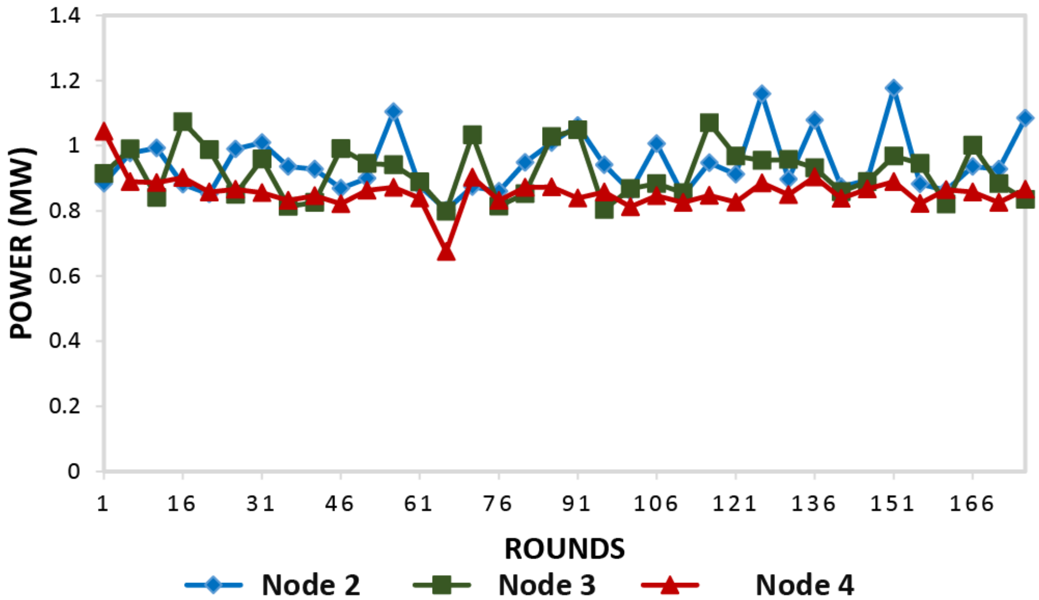

Figure 4.17: Power consumption of the last three nodes (LTH approach) when the length of the pipeline is 950m and the number of the deployed sensors is 30

In addition, figure 4.18 represents the cumulative power consumption of all transactions in the same approach. We can notice that the power consumption increases steadily as the rounds increases. In this approach, each sensor node keeps consuming approximately the same power for all rounds during the operational time.

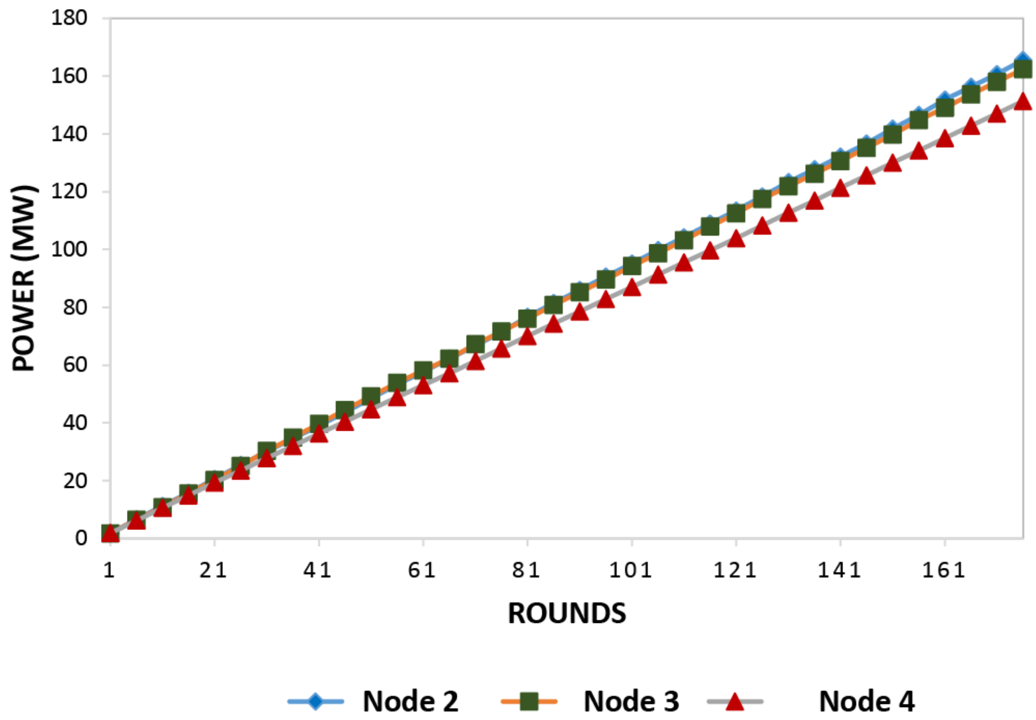

Figure 4.18: Cumulative power consumption of the last three nodes (greedy approach) when the pipelines length is 950m and the number of the deployed sensors is 30

In contrast, the power consumption of the last cluster in case of EDEM approach is depicted in the figures 4.19 and 4.20, respectively. We can notice that the power consumption of each node among the cluster varies over the time. That's because the node that is in charge to be a CH for a period, then it works as a normal node. Also, we can observe that the cumulative power consumption at the end of the experiment approximately reach to steady values for all cluster nodes. While in greedy approach, the last sensor node still consumes the highest power all the time.

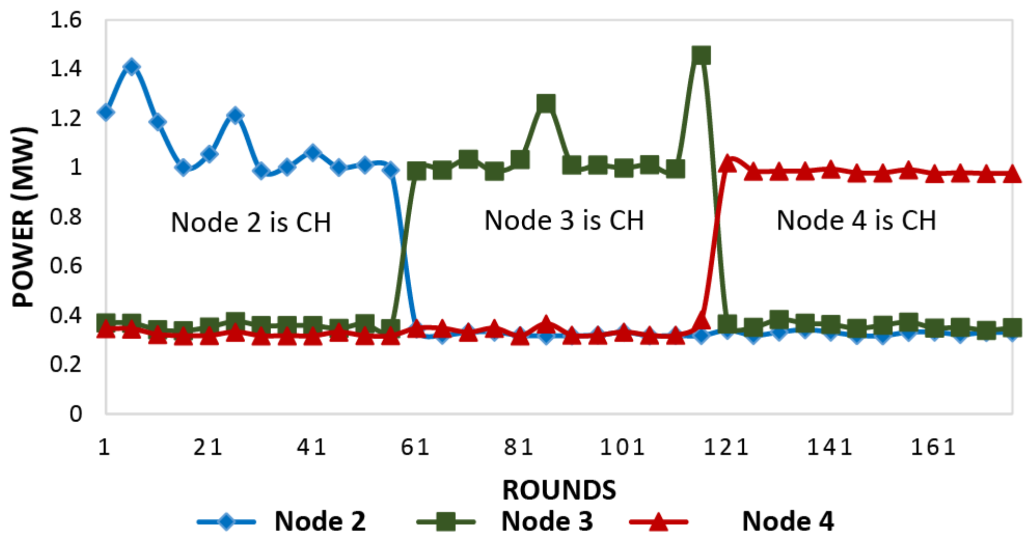

Figure 4.19: Power consumption of the last cluster in EDEM approach when the pipelines length is 950m and the number of the deployed sensors is 30

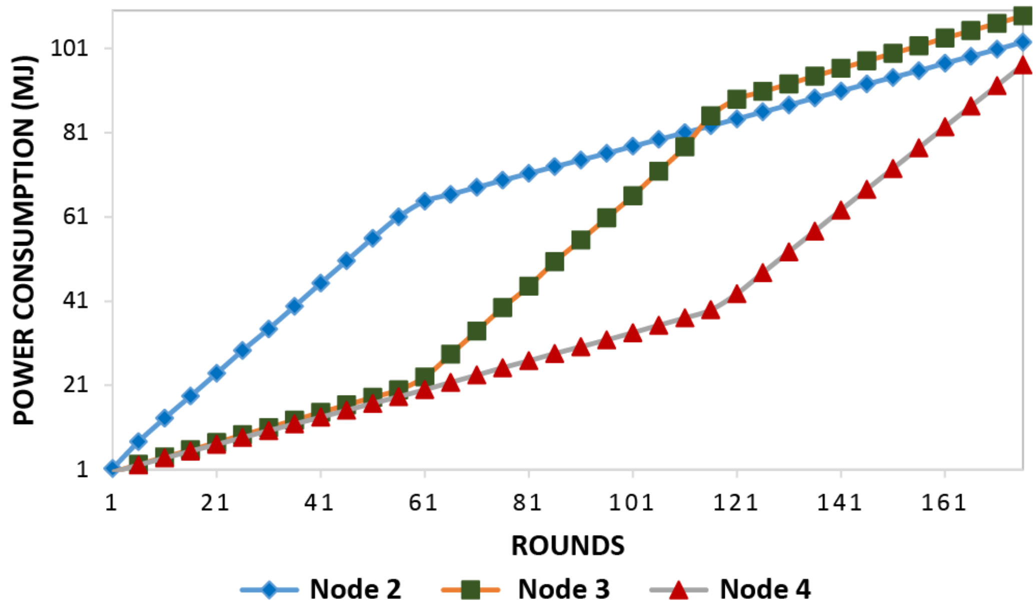

Figure 4.20: Cumulative Power consumption of the last cluster in (EDEM approach) when the pipelines length is 950m and the number of the deployed sensors is 30

Moreover, we can turn to analyze the details of the power consumption of each stage on sensor nodes. For example, the whole transaction is shown in figs 4.21 and 4.22 could be roughly divided into four stages, the transmitting stage (TX), the receiving stage (RX), LPM stage and CPU stage. The first peak of the TX and CPU stages indicates the wake up of the micro-controller unit, and the chip starts to do some pre-processing work, including message packaging and some hardware initiation. Firstly, for the greedy approach, each stage still works at the same power level and consumes more energy all the time as depicted in fig 4.21. On the other hand, the power consumption varies from stage to another over time. If the sensor node is a CH, it consumes a high power otherwise, it consumes less power. This behavior leads to conserving the energy.

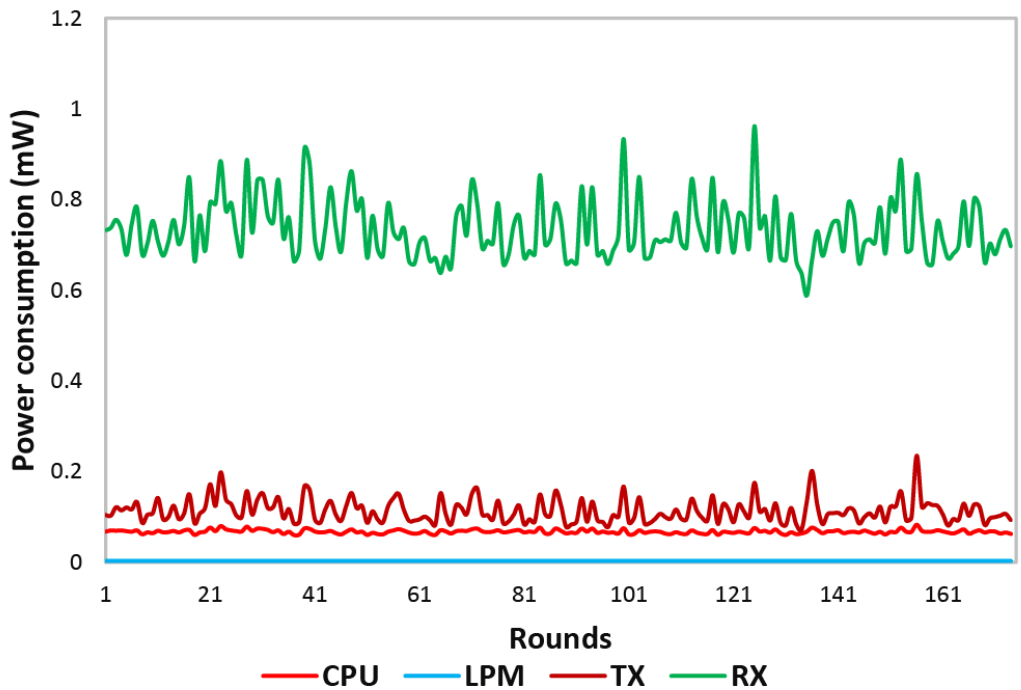

Figure 4.21: Power consumption of each stage of the last sensor node (Greedy approach) 1- The CPU stage 2- The LPM stage 3- The Transmission stage (TX) 4- The Receiving stage (RX)

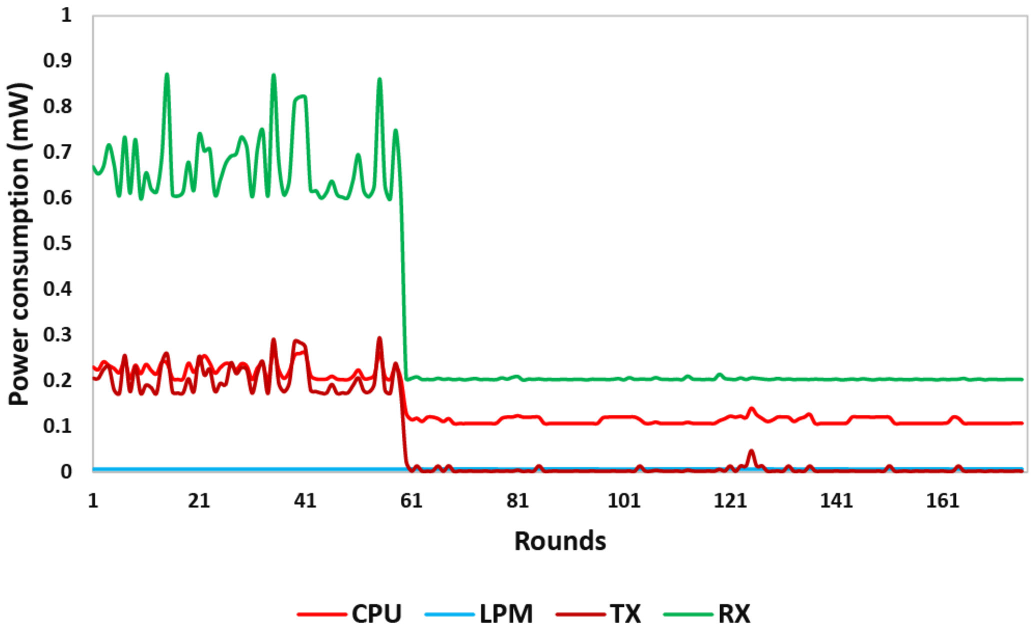

Figure 4.22: Power consumption of each stage of the last sensor node (EDEM approach) 1- The CPU stage 2- The LPM stage 3- The Transmission stage (TX) 4- The Receiving stage (RX)

Finally, to verify the results, the experiments have been replicated five times. This repetition refines the observation to enable us evaluating the proposed approach clearly. Fig 4.23 shows the confidence intervals with the mean of average power consumption in these experiments. The confidence intervals are calculated with 95% degree of confidence. It can be noticed that there is an intersection between all experiments with a slight variation.

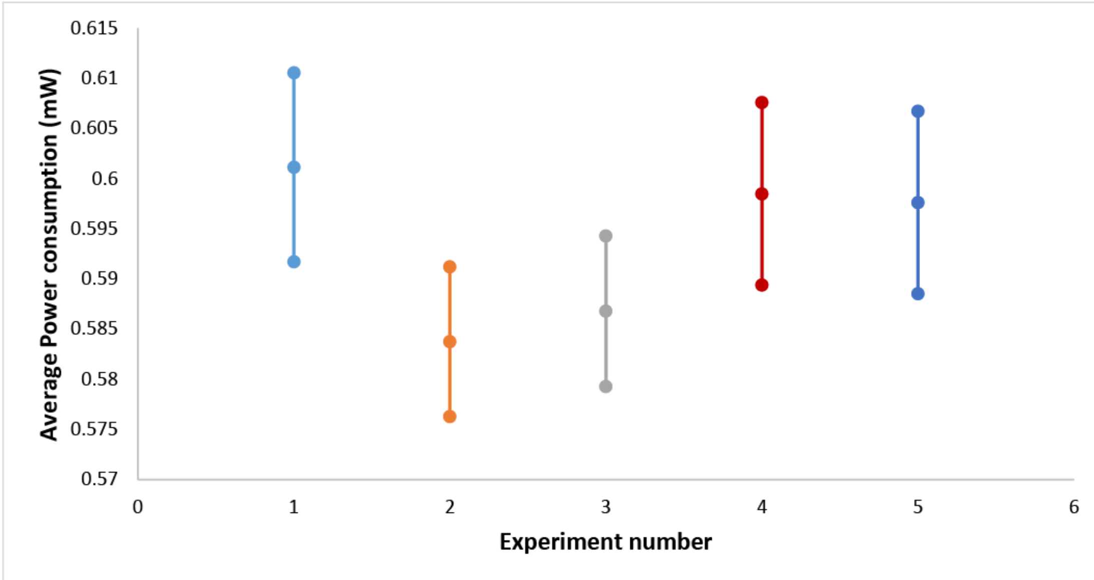

Figure 4.23: Confidence Intervals of the power consumption of the five experiments (EDEM approach) when the length of the pipeline is 950m and the number of the deployed sensors is 30 (with 95% confidence level)

4.6 Conclusion

Node placement in on-line pipelines monitoring application is a critical issue and has a deep influence on the whole network performance due to its effect on its scalability and lifetime. Exploiting the advantages of the clustering techniques, this chapter has investigated the lifetime and the energy consumption with the aim of maximizing the lifetime and reducing the energy consumption. A novel clustering approach has been proposed. Our approach, prominently gathers the sensor nodes based on their power levels to balance the loads on the sensor nodes practically, among the same cluster where all clusters have the same members has been proposed. The simulation experiments have been conducted under several scenarios and the results show 62% increasing in the lifetime compared with the heuristic schemes. Then real experiments have been conducted to validate the simulation results. Our set of experimental studies has been implemented using TelosB motes. The results show that the performance of the proposed approach outperforms the greedy approach and the lifetime can expand to 50%. Also for power consumption, the results show that EDEM approach is very power-efficient and more suitable for linear topology networks.

CHAPTER 5

EQUALLY-DISTANCE DIFFERENT MEMBERS NODE PLACEMENT APPROACH

5.1 Introduction

This approach is considered as an extension to the previous approach (EDEM). In this Approach, each cluster has a different number of sensor nodes based on base station location where the closest to the base station the greatest number of members. The goal of this distribution is 1- enhancing the sensing fidelity 2- prolong the network lifetime 3- reducing the energy consumption because the cluster located far away from the BS using EDEM approach still carries out/transmits a fewer loads while the clusters closer to the BS still carries out/transmits heavier loads so the density of the sensor nodes of these clusters should be increased as the distances get closer to the base station, such that the lifetime is extended by adding few more sensors. In addition, the distance between adjacent clusters remains the same as in the EDEM approach along the length of the pipelines because the maximum transmission range is the same, (i.e. 95m for telosB mote).

As we can notice from the EDEM analysis the sensor nodes placed away from the BS Still retain a very large amount of energy. This energy should be exploited by increasing the SNs in the clusters closer to the BS. This opts to more resources utilization, longer lifetime and higher fidelity.

To precisely understand the procedure of this approach, we are going to model this approach mathematically then we develop a heuristic to execute this approach and derive the optimum number of members in each cluster.

5.1.1 Mathematical Model

The main purpose of this model is to find a reference mathematical formula for deriving the optimal number of members in each cluster with the aim of balancing the power consumption among all clusters. To know the total power consumption of each cluster the equations 4.1, 4.2 and 4.3, explained in chapter 4, are adopted.

Let's set the time $t = 1$. So, the inner power consumption of each cluster can be expressed as:

$$EC_i = \sum_{i=1}^{k-1} i.Pt_i + (i-1).P_R$$

Assign equal distance between sensor nodes within each cluster then

$$Pt_i = P_T$$

$$EC_i = P_T \sum_{i=1}^{k-1} i + P_R \sum_{i=1}^{\mathrm{k}-1} (i-1)$$

By substituting the summation to a fraction from the inner power consumption, this formula can be modeled as:

$$EC_i = P_T \frac{k(k-1)}{2} + P_R \frac{(k-2)(k-1)}{2} \tag{5.1}$$

Also, the power consumption of the Cluster head is:

$$ECH_i = i.k_i.P_C.t + (i.k_i - 1).P_R.t$$

Where K_i is the number of sensor nodes in cluster i.

For simplicity, we denote ECH_i as f_i, So the total energy consumption of the cluster i can be expressed as:

$$E_i = EC_i + f_i \tag{5.2}$$

Due to the unequal members of each cluster, the lifetime can be expressed as:

$$LT_i = \frac{k_i.E_{budget}}{E_i}$$

where E_{budget} is the initial capacity of the sensor node battery and E_i is the total energy consumption of the cluster i.

Substituting E_i by Equation 5.2, LT_i can be expressed as

$$LT_i = \frac{k_i.E_{budget}}{P_T\frac{k(k-1)}{2} + P_R\frac{(k-2)(k-1)}{2} + f_i}$$

As a result, the final formula of the lifetime calculation can be simplified as:

$$LT_i = \frac{2.k_i.E_{budget}}{P_T.k(k-1) + P_R.(k-1)(k-2) + 2f_i} \tag{5.3}$$

Now, we need to find the optimum the k sensor nodes of each cluster that achieve the maximum lifetime. For the optimal K^* sensors, we can expect the following convex:

$$LT_{i-1}(K^*{-}1) < LT_i\,(K^*) > LT_{i+1}(K^*{+}1)$$

From equation 5.3, the lifetime of K^* can be expressed as

$$LT_i(k^*){=}\frac{2k^*E_{budget}}{P_Tk(k^*{-}1){+}P_R(k^*{-}1)(k^*{-}2) + 2f_i}$$

Also, likewise, the lifetime of $K^* + 1$ can be expressed as

$$LT_{i+1}(k^*{+}1){=}\frac{2(k^*{+}1)E_{budget}}{P_Tk(k^*{-}1+1){+}P_R(k^*{-}1+1)(k^*{-}2+1) + 2f_i}$$

$$=\frac{2(k^{*}+1)E_{budget}}{P_T k(k^{*})+P_R(k^{*})(k^{*}-1)+2f_i}$$

We need to satisfy the following condition:

$$\frac{2k^{*}E_{budget}}{P_T k(k^{*}-1)+P_R(k^{*}-1)(k^{*}-2)+2f_i} > \frac{2(k^{*}+1)E_{budget}}{P_T k(k^{*})+P_R(k^{*})(k^{*}-1)+2f_i}$$

We have solved these Inequalities as Quadratic Equations then solve them by using the quadratic formula:

And we get

$$k^{*}\geq\frac{-(P_T+P_R)+\sqrt{(P_T+P_R)^2+8(P_R+f)(P_T+P_R)}}{2(P_T+P_R)}$$

This can be simplified to get:

$$k^{*}\geq\sqrt{\frac{1}{4}+\frac{2(P_R+f)}{(P_T+P_R)}}-\frac{1}{2} \tag{5.4}$$

Also by applying the same steps for the other side of the inequality. We get

$$k^{*}\leq\sqrt{\frac{1}{4}+\frac{2(P_R+f)}{(P_T+P_{\mathrm{R}})}}+\frac{1}{2} \tag{5.5}$$

We can notice that the two equations are very similar except the last part. So, the optimal number of sensor nodes will be bounded between the values resulting from these equations. These equations are used as a reference model to select the appropriate number of members in each cluster.

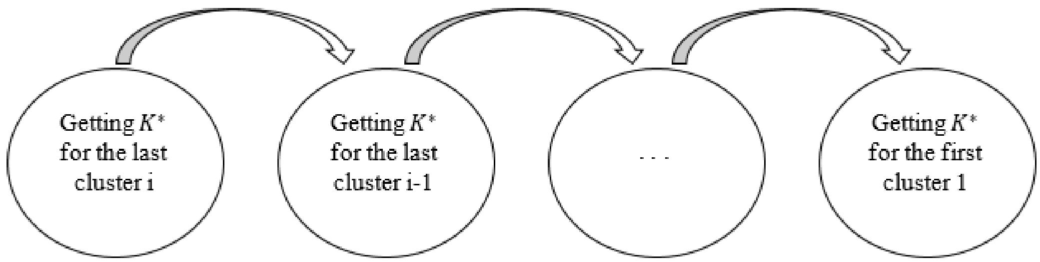

Figure 5.1: EDDM mechanism to find the optimal number of sensors in each cluster

5.1.2 EDDM Heuristic Scheme

As we mentioned before, to balance the energy consumption among the clusters, the number of members should be increased in those nearest to the base station. In what follows, we first formally show that, for two adjacent clusters C_i , C_j the number of members $NMC_i > NMC_j$ where $i > j$. Then, equally-distance different members (EDDM) heuristic scheme will be presented as follows. Algorithm 5.1 explains the EDDM heuristic. We begin by assigning equal members in each cluster then we start optimizing the number of members of the last cluster. For such purpose, we will repeatedly search for the number of sensor nodes that achieves the maximum lifetime. We repeat such scenario for all clusters to ensure that all clusters have the proper number of members. Figure **??** describes this mechanism starting from the last cluster.

Table 5.1: EDDM algorithm to select the optimal numbers of sensor nodes in each cluster

Input: L, and (P_j, R_j) with j = 1, . . ., m; //m=31
Start set optimal k=3, $Fedility_{levels}$=8 //to get the minimum Fidelity
calculate number of clusters $NC = \frac{L}{R_m}$ //the number of clusters
For each cluster $C_i, i = 1, 2, , NC$
  set $M_i = k$ //// number of members
  For each power level P_{no} $where$ $no = 1, 2, 3, , Fedility_{levels}$
    If the number of members in this level can cover the cluster length
      Set the power level of these members to this level, break;
    end if
  end for
  Calculate the expected lifetime of each cluster.
end for
For each cluster,$C_i where i = NC, NC - 1, NC - 1, , 1$;
  Start set k as optimal members;
  For all possible number of members start from $K^* = k + 1$;
    For each power level P_no where $no = 1, 2, 3, , Fedility_{levels}$
      If the number of members in this level can cover the cluster length
        Set the power level of these members to this level; break;
      end if
    end for
    Calculate the lifetime of the cluster C_i $with$ K^* members;
    If the lifetime of C_i $with$ K^* $members > lifetime$ $with$ k members;
      k=K*; set k as an optimal;
    end if
end for

5.2 System Model

The system model explained in section 4.2 in the previous chapter has been adopted in this study with some extensions, especially in the number of sensor nodes assigning for each segment. The number of members in each cluster here is unequal in order to balance the power consumption among different clusters. The density of the sensor nodes of each cluster increases as the distance gets close to the BS. The distance between all clusters is similar and should not exceed the maximum transmission ranges to enable us applying the proposed approach.

5.3 Performance Evaluation

We have conducted extensive simulation experiments examining the performance of EDDM approach. MATLAB has been used to simulate the proposed EDDM approach with different pipelines length in order to be compared to EDEM approach. The adopted lengths start from 950 up to 4750 meters and the same number of sensor nodes for both approaches.

The performance metrics used in this study are the same metrics explained in section 4.4 which are network lifetime, total power consumption and the total sent and forwarded packets.

5.3.1 Results and Analysis

The performance of the two proposed approaches has been investigated under different scenarios. First, we show the effect of both approaches on lifetime to know which approach prolongs the lifetime. From Fig 5.2, we can observe the lifetime using the EDDM approach is 40% longer in all tested scenarios compared with the lifetime using EDEM approach. This is due to the increasing the collaborative sensor nodes in the clusters besides the BS leading to share the loads between these nodes over the time. However, in both approaches, the lifetime decreases dramatically as the length of the pipeline increases, so it is recommended to place a BS every 950 meters, then using another technology to deliver the collected sensor readings to the data center.

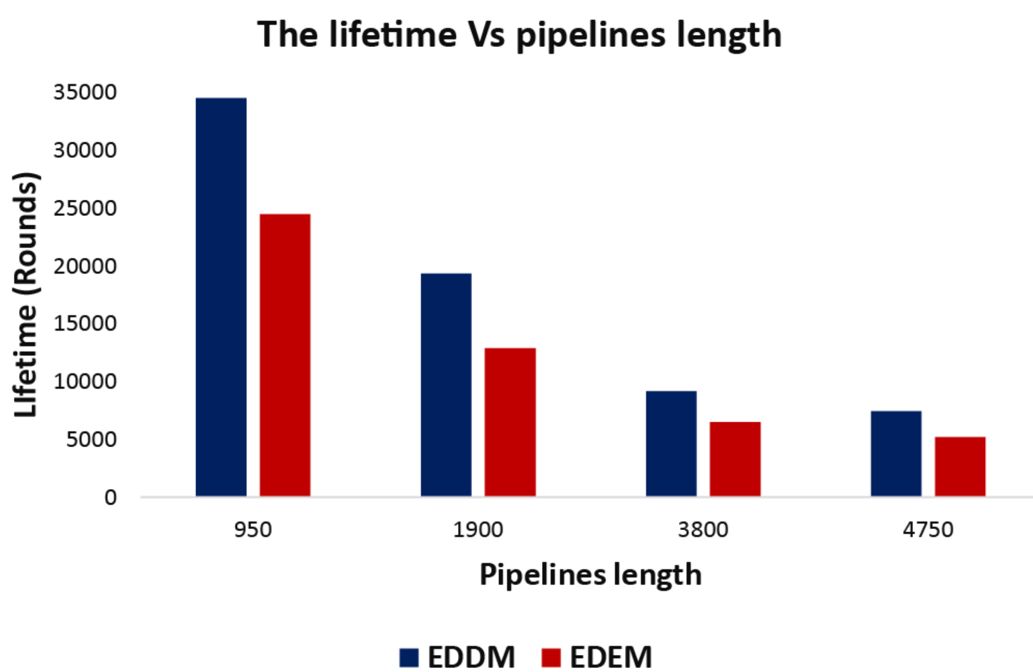

Figure 5.2: The network lifetime when the length of the pipeline is 950, 1900, 3800, 4750 meters

Figure 5.3 presents the total energy consumption in all tested scenarios. The EDDM conserves the power by 35% compared with the power consumption in

EDEM approach because the number of forwarded packets decreases on the clusters besides the BS, while in EDEM approach the same number of packets is sent from all the clusters as the figure 5.4 illustrate.

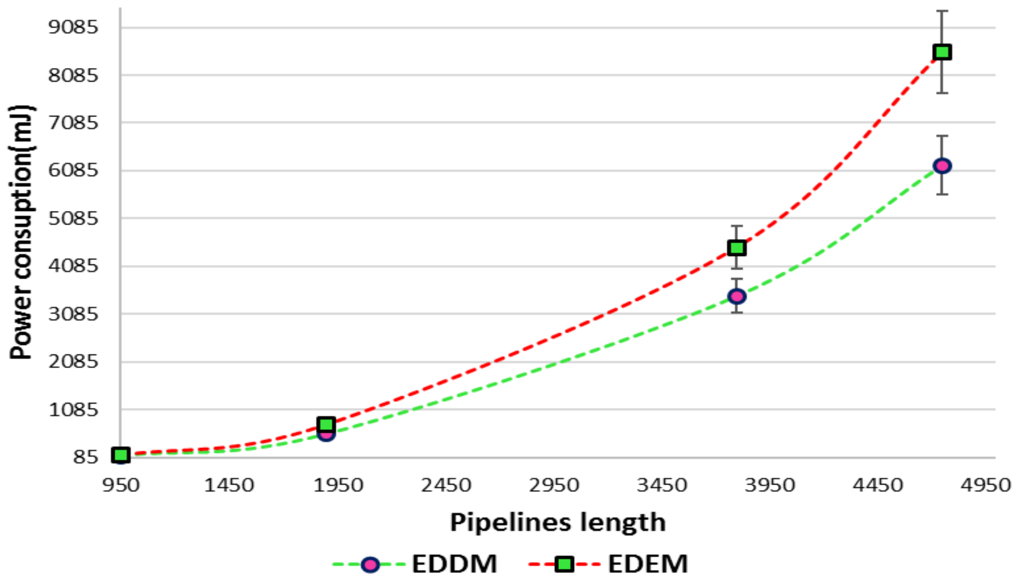

Figure 5.3: The total power consumption when the length of the pipeline is 950, 1900, 3800, 4750 meters

The total number of arriving packets is the last factor to show which approach reduces the terrific better. It can be observed from figure 5.4, the EDDM succeeds to reduce the total packets forwarded by around 13% because of the less number of members of the clusters further from the BS, the less number of forwarded packets.

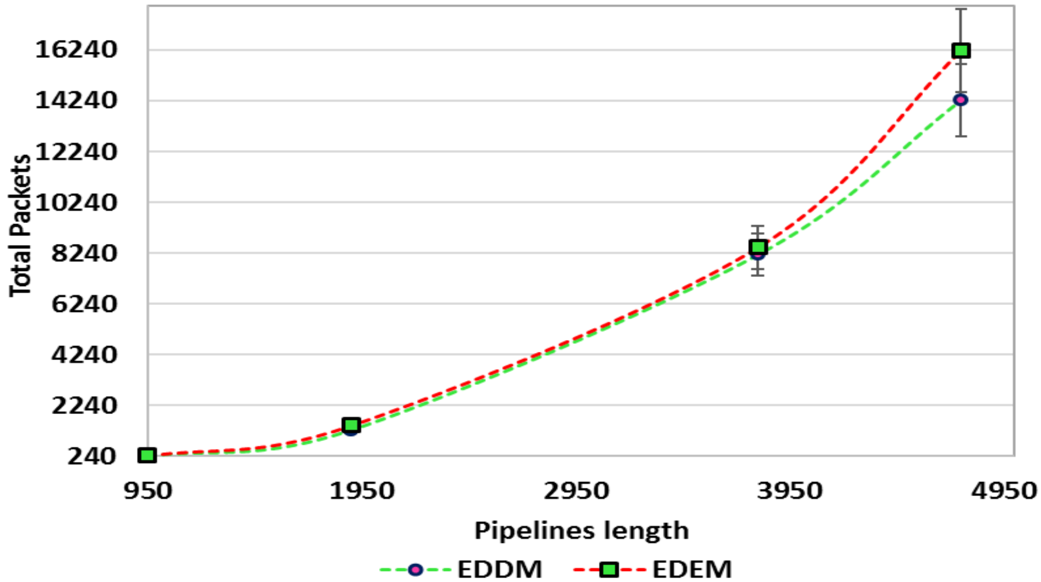

Figure 5.4: The Total sent and forwarded packets when the length of the pipeline is 950, 1900, 3800, 4750 meters

5.4 Experimental Study

In this section, the two proposed clustering approaches are implemented using real hardware devices in the outdoor environment: Equal distances equal members, and equal distances different members. For EDEM approach, it has been implemented here by assigning four members in each cluster to be compared to the EDDM approach. For the used motes, we have used the TelosB motes as in the previous chapter, but the deployments of these motes are different as explained in section 5.4.1. After several pre-experimental tests, detailed experimental parameters are set according to the pre-test results. These parameters are shown in table 5.4.

Table 5.2: Real Experiment Parameters of EDEM and EDDM approaches

Parameter	Value
ContikiOs	2.7
The pipelines length for both approaches	950 meters
Tx current consumption	8.5-17.4 mA
Rx current consumption	18.8 mA
CPU current consumption	1.8 mA
LPM current consumption	5.1 uA
Voltage	3 V
nominal capacity	2600 mAh

In these experiments, the sensor node sends its reading periodically to the base station. The operating code has been uploaded using Contiki operating system because it introduces a power-saving duty cycling protocol on the MAC layer and moves it to a new layer above the MAC layer, called the Radio Duty Cycling layer. If a device is running ContikiMAC over normal 802.15.4 MAC layer, it will periodically activate the RF radio and check if the channel listening is busy. If there are packets in the channel, the radio will be kept on until it receives the packet and quickly turn to sleep again. On the other hand, the sending node will also re-transmit the packet to send several times before it receives the response from the target[52].

5.4.1 Node Deployment

There is a total number of 46 sensor nodes in this test. One of these nodes acts as the base station and it is connected to the laptop in a fixed place. The other 45 nodes are deployed in the outdoor environment in order to cover the intended distance. For EDEM approach, the nodes are spread based on its assigned power level, which is all members other than CH set to power level 4 while all CHs set to power level 31. For EDDM approach, the sensor nodes are deployed based on the assigned power level in each cluster as computed by algorithm 5.1. Table 5.3, presents the details in which the sensor nodes are deployed and the power levels of each cluster members that are assigned.

Table 5.3: EDDM node distribution details

Cluster Id	1	2	3	4	5	6	7	8	9	10
Number of members	3	3	3	3	3	3	5	6	7	9
Assigned Power level	8	6	6	6	6	6	5	5	5	5

5.4.2 Results

The performance of the proposed two approaches has been investigated to explore the effect of using real sensor nodes in outdoor environments. We show the effect of both the EDEM placement approach and EDDM placement approach in the lifetime and the total energy consumption. The major objective of the power consumption test is to estimate the battery life of these embedded devices and try to make some preferences, in which the optimal approach that conserves the total energy consumption and thus increases the battery lifetime.

Here, we focus on the last cluster of the networks in determining the lifetime because it carries the heaviest load and hence it consumes more power.

For the total energy consumption using EDEM approach, figure 5.5 depicts the energy consumption of nodes 2-5 which are formed the last cluster based on EDEM approach. Also from figure 5.6 We can observe that the cumulative power consumption is balanced among these nodes at the end of the experiment time.

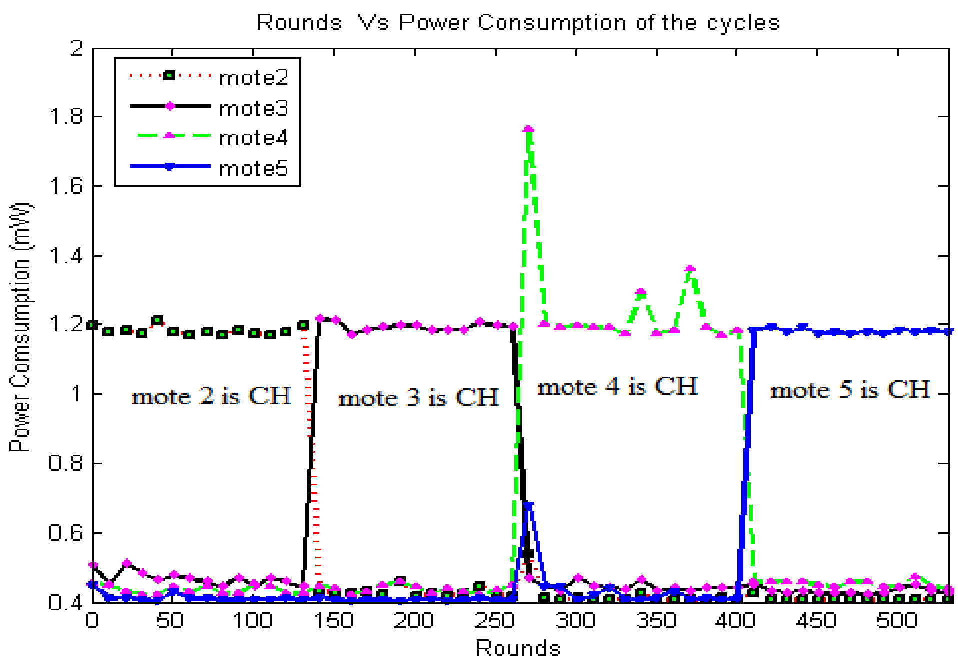

Figure 5.5: Power consumption Vs cycles (EDEM approach when the pipelines length is 950m and the number of nodes is 45)

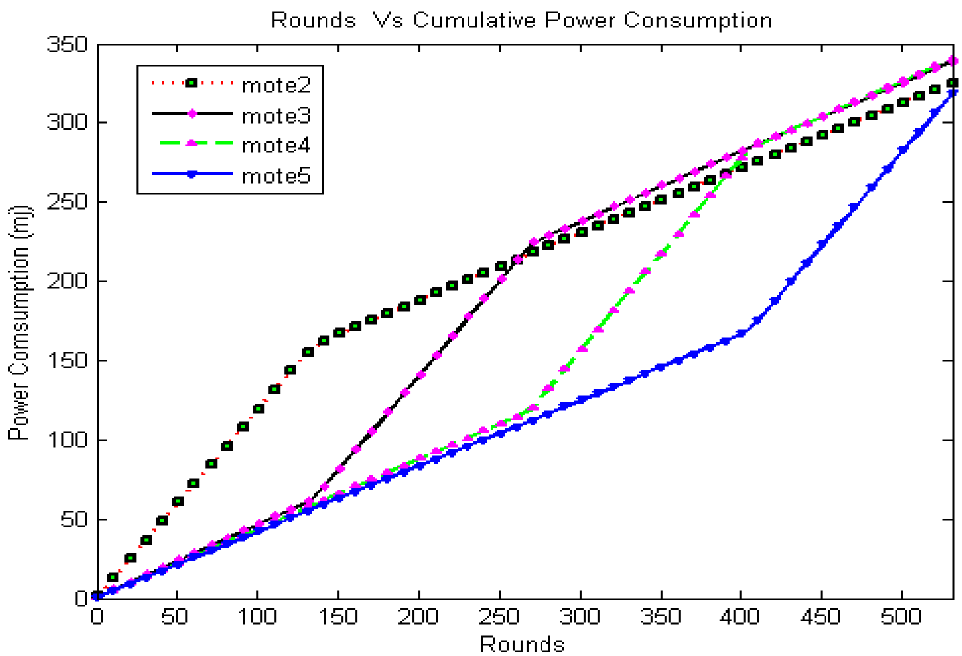

Figure 5.6: Cumulative power consumption Vs Cycles (EDEM approach when the pipelines length is 950m and the number of nodes is 45)

In contrast, the number of sensor nodes of the last cluster based on EDDM approach is 9 nodes because this approach increases the density of the nodes nearest to the BS.

Figs 5.7 and 5.8 illustrates the power consumption of the cycle versus the number of rounds. The CHs are elected alternatively over time as we can notice from these figures where the energy consumption is only high when the sensor node is a leader. In addition, the EDDM approach conserves the power consumption by 35% compared with the power consumption in EDEM as we can notice from figures of the cumulative power consumption in both approaches.

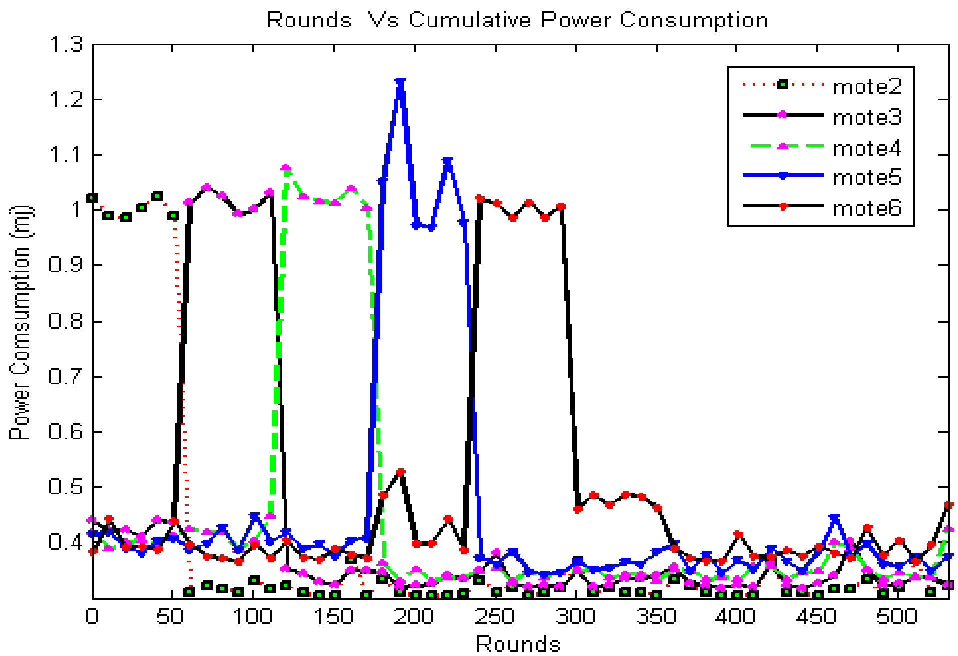

Figure 5.7: The Power consumption (EDDM approach when the length of the pipeline is 950m and the number of nodes is 45) nodes 2-6

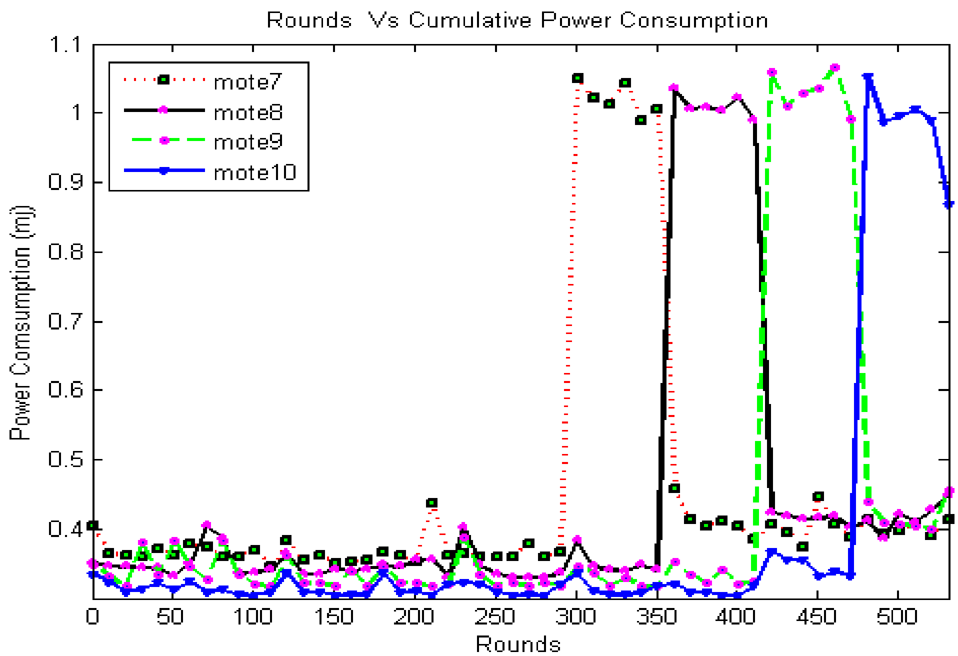

Figure 5.8: The power consumption (EDDM approach when the length of the pipeline is 950m and the number of nodes is 45) nodes 7-10

In figure 5.9 and figure 5.10, the cumulative power consumption from the beginning of the experiment to the end is presented. We can observe that the power reaches approximately to the same point due to the loads balancing among all cluster members. Compared to the cumulative power consumption in EDEM approach, there is a power saving in all sensors due to the distribution of loads over the time.

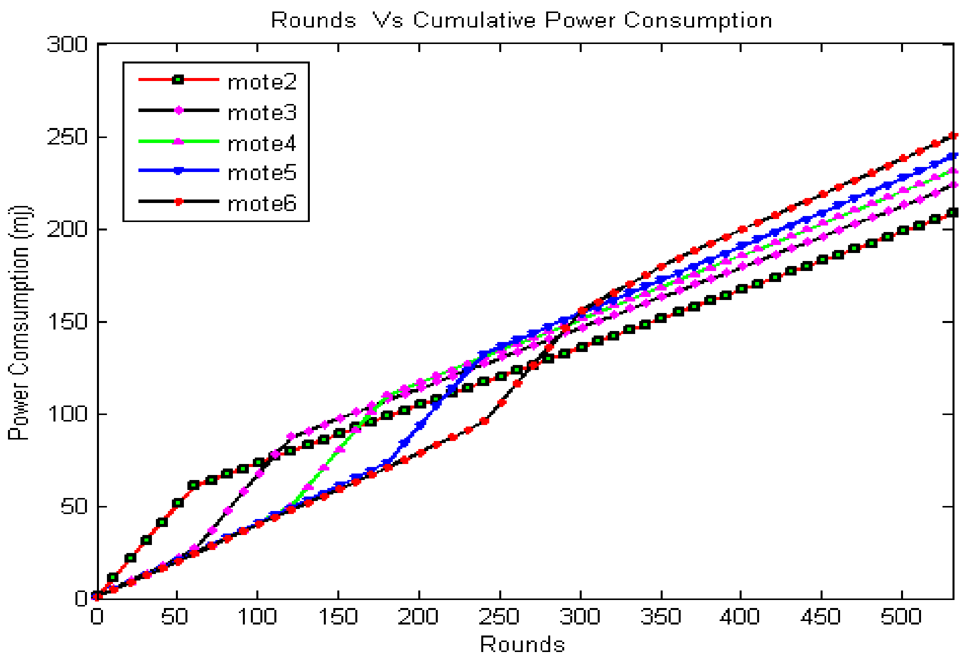

Figure 5.9: Cumulative power consumption The Power consumption (EDDM approach when the length of the pipeline is 950m and the number of nodes is 45) nodes 2-6

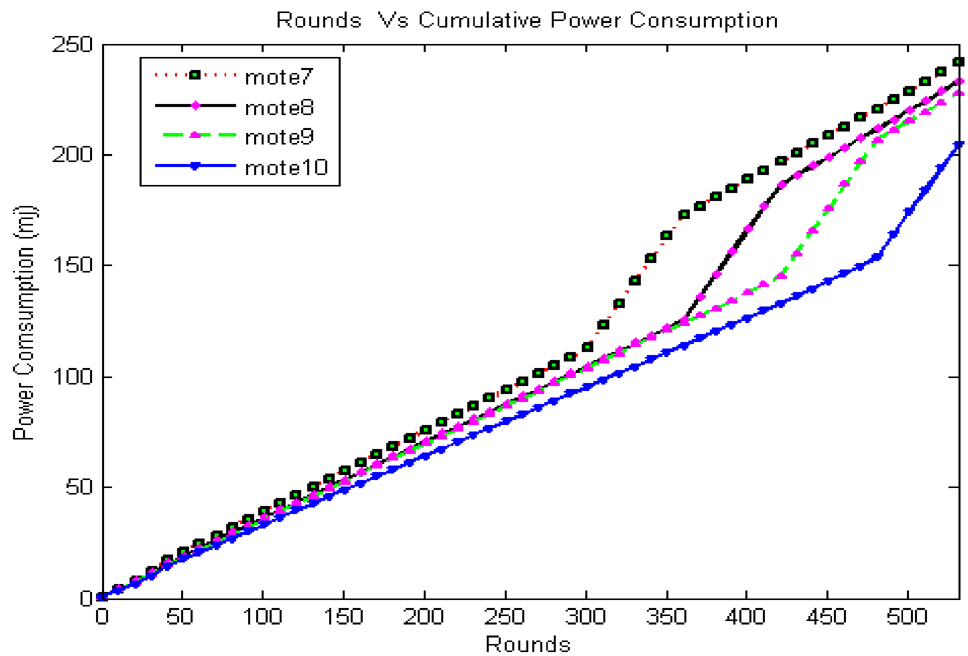

Figure 5.10: Cumulative power consumption (EDDM approach when the length of the pipeline is 950m and the number of nodes is 45) nodes 7-10

Figure 5.11 describes the lifetime of both approaches. The lifetime can be extended in case of using the EDDM approach since the loads are shared among a large number of members besides the BS. The lifetime increases by 36% compared to that in EDDM.

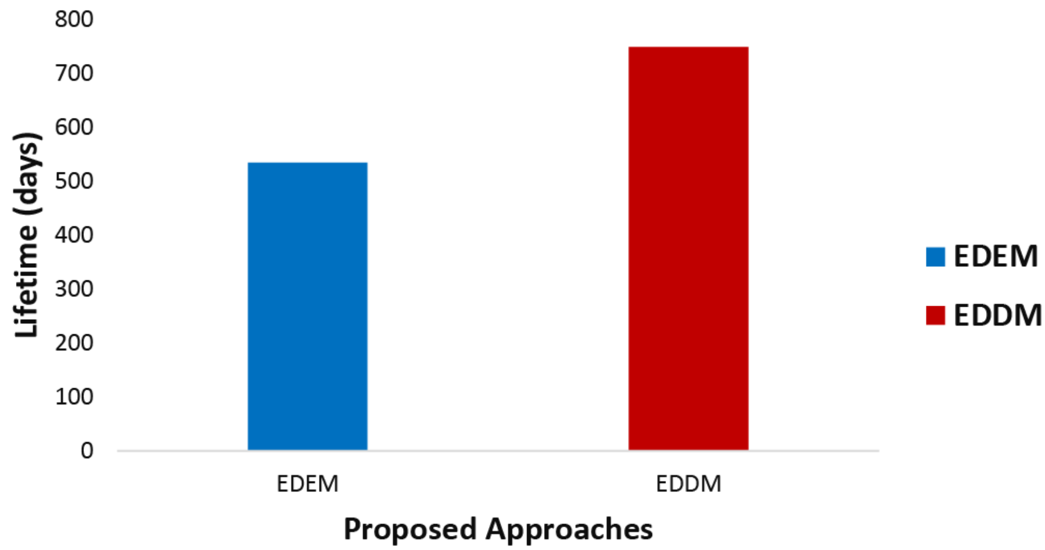

Figure 5.11: The lifetime of the two proposed approaches when the length of the pipeline is 950m and the number of nodes is 45

Overall, the performance of EDDM approach outperforms such performance of EDEM approach.

Finally, to verify the results, the experiments have been replicated five times. This repetition refines the observation to enable us evaluating the proposed approach under different conditions. Fig 5.12 shows the confidence intervals with the mean of average power consumption in these experiments. The confidence intervals are calculated with 95% degree of confidence. It can be noticed that there is an intersection between all experiments with a slight variation all replications.

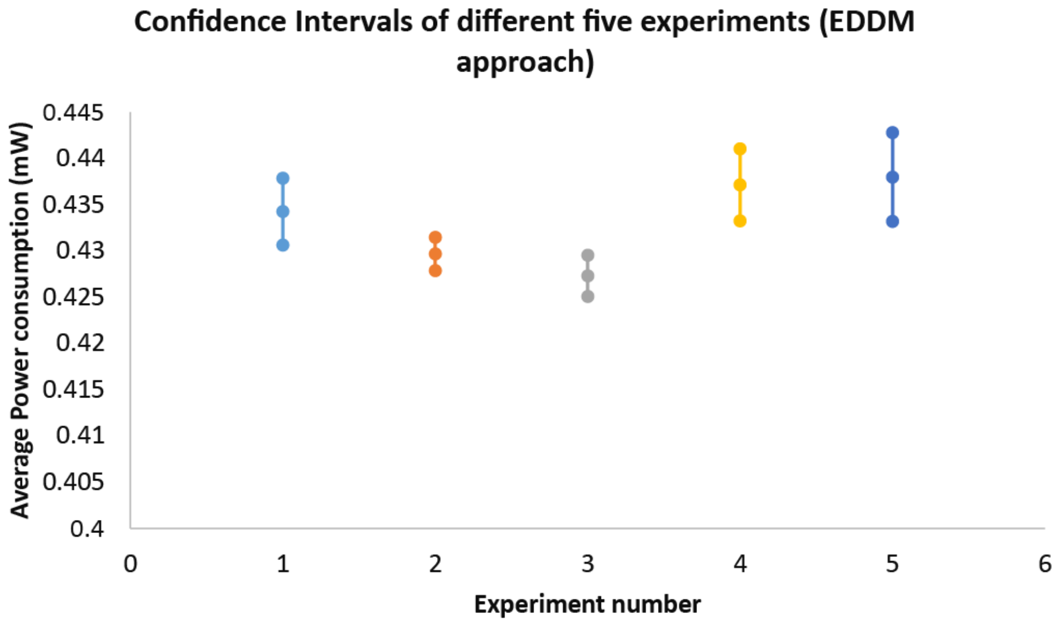

Figure 5.12: Confidence intervals of five different experiments using EDDM approach when the length of the pipeline is 950m and the number of nodes is 45 (with 95% confidence level)

5.5 Conclusion

Secondly, equally space different members (EDDM) which each cluster has a different number of sensor nodes has been deeply investigated. In this approach, a mathematical solution is proposed to calculate the optimal number of members required to cover the area of each segment. Our mathematical, simulation and real experiments have been used to validate each other and prove the reliability of this approach. The obtained simulation results reveal that this approach prolongs the network lifetime by up to 40% and reduce the power consumption by

39% compared to the first approach EDED. In addition, the results of real experiments reveal an increased by 36% in the lifetime and this approach conserves the power consumption by 39% compared with EDEM approach.

CHAPTER 6

CONCLUSION AND FUTURE WORK

In this work, the sensor placement problem in wireless sensor network used in pipelines monitoring system has been studied with the goal of maximizing the network lifetime, minimizing the power consumption and obtained the required fidelity. We have adopted a realistic CC2420 power model and it has been investigated under equal-power placement scheme where the energy is intended to be balanced. We have improved two greedy heuristic schemes which are proposed on [4] based on real measurements of the transmission ranges of all 31 power levels. The real experiment has been carried out to measure the transmission ranges for all 31 power levels that are supported in this model. Extensive simulation and real experiments have been conducted to evaluate the performance of two greedy placement approaches. The results reveal good improvements in the lifetime and total energy consumption. Also, the results obtained from the real experiments proved that using all 31 power levels improved the lifetime up to 23% compared to those using only the 8 power levels. The real experiments validate the obtained results with little differences due to some additional power consumption.

Then, taking the advantage of the clustering techniques, we have investigated the lifetime and the energy consumption with the aim of maximizing the network and reducing the power consumption. Two novel clustering approaches have been proposed. Our approaches prominently, gather the sensor nodes based on their power levels to balance the loads on the sensor nodes practically, among the same cluster. Firstly, equally spaced equally members approach (EDDM) where all clusters have the same members has been conducted. The simulation and real experiments have been achieved and the results show the lifetime, increasing by 62 % than the heuristic schemes. Secondly, equally space different members (EDDM) where each cluster has a different number of sensor nodes has been investigated. In this approach a mathematical solution that calculates the optimal number of members that are required to cover the area of each segment. Our mathematical, simulation and real experiments have been accomplished to prove the reliability of this approach. The obtained simulation results reveal that this approach prolongs the network lifetime by up to 40% compared to the first approach EDED while the results of the real experiment show a 36% lifetime enhancement. Also for power consumption, the results show that both approaches are very power-efficient and more suitable for linear topology networks. In overall, the EDEM approach is recommended if the cost is the main factor, because the number of members is equal in all clusters while the EDDM is recommended if the lifetime is the main objective due to its ability to prolong the lifetime and balance the power consumption among all clusters.

As for future improvements, the following can be used as a guidance for future improvements.

1. Apply the proposed approaches to test the fidelity in more complicated scenarios and a real system to investigate the sensing range alongside with the transmission ranges.

2. Extend the proposed approach to be combined with other technologies (i.e. Wifi) at the end of each segment to limit the distance between the furthest sensor nodes and the base station.

3. Validate the proposed approaches on the real leak detection system under different platform hardware devices would give a great insight of their performance in a real environment.

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  1. A. Al-baseer, G. Bin, and A. Bawazir, Multi-hop Wireless Network: A Comparative Study for Routing Protocols Using OMNET ++ Simulator, Journal of Ubiquitous Systems Pervasive Networks, vol. 7, no. 1, pp. 2934, 2016.
  2. U. Baroudi, A. Albaseer, Anomaly Resilient Node Placement Approach for Pipelines Monitoring, 2017 International Wireless Communications and Mobile Computing Conference (IWCMC), 2017 (Accepted).
  3. A. Albaseer, S. Member, and U. Baroudi, Clustering-Based Node Placement Approach for Water Pipelines monitoring, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS (Ready to be Submitted)